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Loliolide - the most ubiquitous lactone

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ABSTRACT

The searching for biologically active compounds produced by living organisms led to the discovery of a number of compounds with more or less complicated structure. One of the simplest molecules are monoterpenoid lactones and loliolide is the most common among them.

Loliolide was found in animals (insects) and plants (flowers, shrubs, trees) both terrestrial and marine, such as algae and corals. Many years of research on plants used in traditional folk medicine of different countries have led to the conclusion that this compound has a variety of biological properties such as anti-cancer, antibacterial, antifungal and antioxidant ones. Moreover, plants containing loliolide are used in alternative medicine in treatment of diabetes and depression.

It is extremely interesting that this lactone also affects the behavior of ants as well as the development of certain plants (allelopathic activity). However, sometimes there are side effects as in the case of structural analogues of loliolide contributing to extinction of tropical coral.

KEY WORDS: monoterpenoid lactones, loliolide, biological activity fungi, HGT

Introduction

The world around us is full of a wide variety of organic compounds produced by both plants and animals. An important group among them are terpenoids (Grayson 1996, Grayson 1997, Grayson 2000, Molnár *et al.* 2010), derived from terpenes. Terpenes are composed of interconnected isoprene particles (consisting of 5 carbon atoms) which results in the fact that these particles of terpenes are composed of 5, 10, 15, etc. carbon atoms. Compounds structurally related to the terpenes, but constructed from a number of carbon atoms that is not a multiplication of 5 are called terpenoids. A common feature of their structure is oxygen, both in the form of hydroxyl groups and lactone rings. The simplest structural molecules containing both the lactone ring and the hydroxy group are called monoterpenoid lactones (Ragas *et al.* 2005, Ahmed *et al.* 2004, Garg & Agarwal 1994, Fukushima *et al.* 1998, Wong & Bron 2002, Chen *et al*. 2010).

The most common representative of monoterpenoid hydroxylactones, loliolide (**1**) (Fig. 1) consisting of 11

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carbon atoms, is common in plants and animals, both terrestrial and marine. Despite simple structure loliolide shows a broad spectrum of biological activity which, combined with its ubiquity, makes it a very interesting compound.

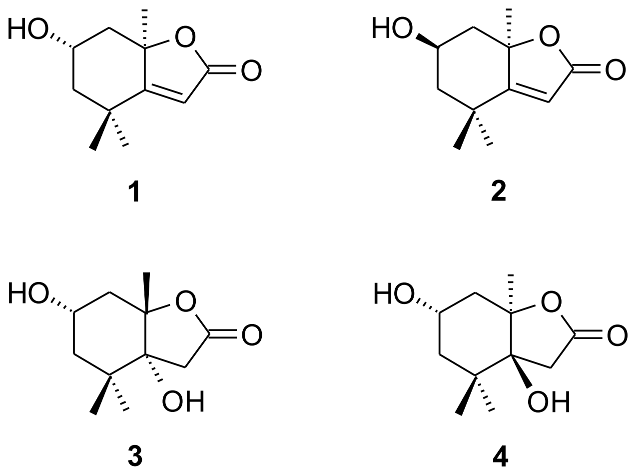

Figure 1. Loliolide and its derivatives.

Occurence of loliolide and its derivatives

Loliolide (**1**) was identified for the first time in English Ryegrass *Lolium perenne* in 1964 (Hodges & Porte 1964). Then it was discovered in bodies of queens of the red ant *Solenopsis invicta*, in which it is one of pheromones that enforce obedience to the queen's attendants (Rocca *et al*. 1983). In brown algae *Sargassum crassifolium* living in the seas stereoisomer epiloliolide (**2**) (Fig. 1) (Kuniyoshi 1985) was found beside loliolide. Over the years loliolide was found in many organisms. Sometimes, in addition to loliolide (**1**) and the aforementioned epiloliolide (**2**), dihydroxy derivatives of loliolide were also noted (**3, 4**) (Fig. 1).

Loliolide (**1**) and its derivatives are usually present in small quantities. Their amount ranges from $5.8\cdot10^{-5}$ % to $8.0\cdot10^{-4}$ % of dry weight of lactone in the case of plants while in marine organisms it averages between $2.0\cdot10^{-4}$ % and $3.0\cdot10^{-3}$ % of lactone in dry matter. Therefore extraction and purification of lioliolide is very complicated, labor-intensive and expensive. First step parts of plants are subjected to extraction with EtOH, EtOAc, MeOH or CH_2Cl_2. The obtained extract after evaporation of a solvent is suspended in H_2O or organic solvent and extracted again. The second extract is fractionated by silica gel column chromatography. Succeeding fractions are subjected to several chromatographic runs on silica gel column or preparative HPLC. After all these steps pure loliolide is obtained in mg yield (for example 20 mg from 1.3 kg of raw material).

Loliolide (**1**) and its isomer - epiloliolide (**2**) have been identified in many plant extracts. Their sources listed in order of amount of lactone are given in Table 1.

Many years of research on plants used in folk medicine of different countries have brought a lot of evidence about very common occurrence of loliolide, and information about its various biological properties.

The researchers in Japan found that loliolide (**1**) was one of the compounds present in common purple loosestrife (*Lythrum salicaria* L.), which was known and used for many years in medicine. It exhibits astringent, antipyretic, anti-inflammatory and vasodilatory effects (Fujita *et al.* 1972).

Table 1. Loliolide (**1**) and epiloliolide (**2**) occurring in land plants.

Compound	The source of origin	The isolated amount of loliolide in% of dry matter
(1)	The roots of *Rauvolfia yunnanensis Tsiang* which is a traditional medicinal plant in China (Geng & Liu 2008)	$8.3 \cdot 10^{-4}$
(1)	Persian speedwell (*Veronica persica* Poir.) from the *Plantaginaceae* family, growing in south-east Asia (Sarker *et al.* 2000)	$6.2 \cdot 10^{-4}$
(1)	Hydrilla (*Hydrilla verticillata* (L. f) Royle) belonging to the family *Hydrocharitaceae* from China (Xiao *et al.* 2007)	$5.6 \cdot 10^{-4}$
(2)	Flower plant *Eirmocephala megaphylla* of northern Argentina (Borkosky *et al.* 1996)	$5.0 \cdot 10^{-}$
(1)	*Salvia divinorum* from the family *Lamiaceae* occurs endemically in the Sierra Mazatec in Mexico at altitudes 300–1800 m above sea level (Valde`s 1986)	$4.4 \cdot 10^{-4}$
(1)	Cornflower *Centaurea Conifera* belonging to the family *Asteraceae* from Spain (Fernandez *et al.* 1995.)	$2.9 \cdot 10^{-4}$
(1)	Leaves of *Schefflera taiwaniana*, plant from the *Araliaceae* family, growing in Taiwan (Kuo *et al.* 2002)	$6.0 \cdot 10^{-5}$
(1)	*Athyrium yokoscense* which is a species of fern in the family *Athyriaceae*, growing in Japan, especially in areas contaminated with heavy metals, around the mines and smelters (Kurokawa *et al.* 1998)	$1.0\ 10^{-5}$
(1)	Shrub *Yerba mate* from South America (Da Costa *et al.* 2008)	no data

Loliolide (1) was found in the extract from heliotrope leaves. Heliotrope *Heliotropium angiospermum* is a shrub from the south-eastern Mexico, belonging to the B*oraginaceae* family. It is used as an anti-inflammatory agent, it accelerates wound healing and is also applied to treat dysentery and diarrhea (Erosa-Rejón *et al*. 2009).

Researchers from Brazil found that lactone loliolide (1) isolated from dried leaves of burdock exhibited anti-proliferative activity with respect to the colon adenocarcinoma cell Caco-2. The study was inspired by the fact that the greater burdock (*Arctium lappa* L.) belonging to the *Asteraceae* family, found throughout the world, exhibits antitumor activity against a number of cell lines (Machado *et al*. 2012).

Powdered roots of common sowthistle (*Sonchus oleraceus* L.) growing in Egypt proved to be another source of loliolide (1). Sowthistle comes from the *Asteraceae* family, commonly occurring in Europe, Asia and North Africa, where it is widely regarded as a weed. It turned out, however, that even the weed may be useful. *In vitro* tests showed that loliolide (1) highly cytotoxic to the mouse lymphoma cell line L5187Y (ED50 = 4.7 mg/ml) and exhibited antibacterial activity against strains of *Bacillus subtilis*, *Escherichia coli*, *Staphylococcus aureus* and *Neisseria gonorrhoeae* (Elkhayat 2009).

Lactone loliolide (1) was also found in the Philippine bush *Malachra fasciata*. This shrub, belonging to the *Malvaceae* family, is also known for its anti-cancer properties. Therefore, the tests were conducted to investigate antimutagenic properties of this plant, the properties that were closely associated with the former ones. It was found that loliolide (1) occurring in this plant, given to mice at a dose of 14.8 mg/kg reduced the number of micronucleated polychromatic erythrocytes induced by mitomycin C by 64.4%. This indicates that it is in fact antimutagen (Ragasa *et al*. 1997).

Loliolide (1) was also found in the Mexican plant called *Penstemon campanulatus* (Cav.) Willd. belonging to the *Plantaginaceae* family. Its antibacterial activity (1) against: *Staphylococcus aureus*, *Staphylococcus epidermidis*, *Escherichia coli*, *Enterobacter cloacae*, *Klebsiella pneumoniae* and *Pseudomonas aeruginosa* strains was found (Zajdel *et al*. 2012).

Loliolide (1) was also detected in the extract of dried leaves of the Philippine tree *Pterocarpus indicus*. Extracts from leaves, wood, bark and roots of this tree have been used among the local population as a medicine for various ailments such as ulcers, diarrhea and dysentery. Testing the effects of loliolide (1) it was found that this compound had a low antibacterial activity against strains of *Pseudomonas aeruginosa* and *Escherichia coli*. It also has moderate antifungal activity against *Candida albicans* and *Aspergillus niger* (Ragasa *et al*. 2005).

Loliolide (1) was found in the leaves of white mulberry (*Morus alba* L.), a species of small deciduous trees of the *Moraceae* family. White mulberry leaves stabilize blood sugar level, reducing its absorption by a human organism and therefore can be used to help type 2 diabetes. *In vitro* studies conducted by researchers from Hungary showed that the dose of 100μg/ml extract of mulberry leaves, the dominant component of which (40.3%) was loliolide (1) had the same effect as a dose of 50 mg/ml of rosiglitazone, a drug used to treat diabetes (Hunyadi *et al*. 2012).

Lactone loliolide (1) was also found in the extract of dried leaves of *Mondia whitei*, a South African plant, known as Ginger White, used in folk medicine to treat diseases of a nervous system. In addition, its dried roots are believed to be an aphrodisiac by the local tribes. In the *in vitro* studies it was found that loliolide (1) had high affinity for a serotonin transporter, thus demonstrating an anti-depressant characteristic. Since it is not a nitrogenous compound typical for antidepressants, it means that its mechanism of action may be different from those known so far (Neergaard *et al*. 2010).

Loliolide and its plant-plant and plant-animal interactions

The tests of plants in the acquisition of these new valuable substances are not limited to the search for medicaments for humans. Equally important are the findings on interactions between plants or between plants and animals.

Loliolide (1) was isolated from fresh leaf extract of horsetail *Equisetum arvense* occurring in Japan. It was found that 250 ppm of the compound completely inhibited germination of lettuce seeds (Hiraga *et al*. 1997).

Loliolide (1) is also present in Jerusalem artichoke *Helianthus tuberosus* L., which is widespread throughout the world as an edible, forage and decorative plant. It was isolated from this plant growing in the U.S. state of Ohio and the Mississippi River valley. It was found that this compound slightly (15–20%) stimulated accumulation of metabolites involved in plant defense against pathogens (Pan *et al*. 2009).

Loliolide (1) was isolated from an extract of crabgrass *Digitaria sanguinalis* roots. This plant belongs to the *Poaceae* family that occurs in north-eastern China. It exhibited allelochemic activity, on the one hand on the inhibition of soybean root growth, on the other, it stimulated growth of maize shoots (Zhou *et al*. 2013).

Lactone loliolide (1) was isolated from an extract of dried leaves of *Xanthoxyllum setulosum* P. Wilson, a plant occurring in Costa Rica. This plant has been considered in the search for plant protection against pests. It is so because the plant is known to deter ants *Atta cephalotes* (Attini). Loliolide (1) was used for the test with choice for a captive colony of hundreds of ants. The ants were supposed to choose from rye flakes saturated with a solution of loliolide at the concentration of 6.8 mg/g and wheat flakes soaked only with clean solvent. The results showed that the ants definitely chose the cereal without the compound. The authors concluded that this might indicate that loliolide is the sought ant-repellent for these ants (Okunade & Wiemer 1985).

Loliolide found in marine organisms

Looking for new sources of potential medicines people also turned to organisms living in coastal waters, because wide variety of plants and animals, often unknown to science live in seas and oceans.

Dried and powdered brown algae *Sargassum ringgoldianum* subsp. *Coreanum* proved to be a good source of loliolide (1), exhibited antioxidant properties protecting the cell against the harmful effects of free radicals produced by the action of H2O2 (Yang *et al*. 2011).

Loliolide (1) was also extracted from molluscs of the genus *Opisthobranch* living in the Indian Ocean. Tests showed that this compound inhibited the growth of tumor cells of human nasopharyngeal carcinoma KB (ED50 = 10 μg/ml) and murine lymphocytic leukemia P-388 (ED50 = 3.5–22 μg/ml) (Pettit *et al*. 1980).

Epiloliolide (2) with its dihydroderivative (3) were isolated from red algae *Galaxaura filamentosa* occurring on the reefs of Votua (Fiji). These compounds were found during tests on the effects of algal growth combined with a simultaneous extinction of corals on tropical reefs. These lactones were found to inhibit of photosynthesis in coral, causing their deaths, even up to 79% of the population within 24 hours of the contact of alga-coral (Rasher *et al*. 2011).

Loliolide (1) and its dihydroderivative (3, 4) were also found in other marine plants and animals, such as algae or corals which are presented in Table 2.

Summary

Currently, there is growing interest in what our ancestors knew well, that nature is the source of various products valuable for us. Instead of synthesizing often very expensive and complicated compounds, it is better to use the compounds that nature has already created. Lactone loliolide (**1**) is a very simple molecule with a wide variety of properties commonly found in living organisms on Earth, both on land and in water. It should be emphasized that lactone loliolide (**1**) found in many different organisms is always the same compound. This makes its anti-inflammatory, anti-tumor or anti-bacterial activity even more important. However, its beneficial effects in diabetes or depression treatment are also significant. Undoubtedly, further studies of plants used in traditional folk medicine will lead to finding new sources of loliolide and the subsequent discovery of its properties and applications.

Table 2. Loliolide and its derivatives in marine organisms.

Compound	The source of origin	The isolated amount of loliolide in% of dry matter
(1)	Brown algae Cladostephus spongiosus f verticillatus occurring in the Mediterranean Sea and the coastal waters of the Atlantic from Morocco to Ireland (El Hattab *et al*. 2008)	no data
(1)	Brown algae Dictyota dichotomia occurring in the coastal waters of Pakistan (Ali *et al*. 2003, Ali 2012)	no data
(1)	Brown algae Padina tetrastromatica occurring in the coastal waters of India (Parmeswaran *et al*. 1996)	no data
(1)	Green algae Codium Divaricatum Holmes occurring in the coastal waters of China (He *et al*. 2010)	2.0·10-4
(1)	Soft corals Sinularia capillosa from Dongsha atoll (Taiwan) (Cheng *et al*. 2010)	2.0·10-4
(3,4)	Brown algae Undaria pinnatifida from Japanese sea (Kimura & Maki 2002)	1.4·10-3

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Streszczenie

Poszukiwania związków biologicznie aktywnych wytwarzanych przez organizmy żywe doprowadziły do odkrycia wielu związków o mniej lub bardziej skomplikowanej strukturze. Jednymi z najprostszych cząsteczek są laktony monoterpenoidowe, zaś najczęściej spotykanym spośród nich jest loliolid.

Loliolid spotykany jest w organizmach zwierzęcych (owady) i roślinnych (rośliny kwiatowe, krzewy, drzewa) zarówno lądowych jak i morskich takich jak glony lub koralowce. Wieloletnie badania prowadzone nad roślinami używanymi w tradycyjnej medycynie ludowej różnych krajów doprowadziły do stwierdzenia, że związek ten ma różnorodne właściwości biologiczne np. antynowotworowe, antybakteryjne, antygrzybiczne, antyoksydacyjne. Ponadto rośliny zawierające lioliolid są stosowane w medycynie alternatywnej przy leczeniu cukrzycy oraz depresji.

Niezmiernie interesujący jest fakt, że lakton ten wywiera również wpływ na zachowanie mrówek jak i na rozwój niektórych roślin (aktywność alleplopatyczna). Czasami jednak można zaobserwować również działania niepożądane jak w przypadku analogów strukturalnych loliolidu mających swój udział w wymieraniu raf tropikalnych.

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The role of biogeochemical barriers in protecting aquatic ecosystems against pollution in agricultural environment

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ABSTRACT

This review discusses the importance of ecotones with high plant diversity which are highly effective in retaining pollutants and waste. Biogeochemical barriers play a vital role in eliminating biogenic pollutants, pesticides and heavy metals. Belts of rush plants and meadow vegetation considerably expand the accumulation capacity of water bodies and watercourses. The mechanisms responsible for the protective role of biogeochemical barriers involve various processes such as sorption, sedimentation, denitrification and assimilation, which require the coexistence of plants and microorganisms in aquatic ecosystems. Buffer barriers were presented as one of the ecohydrology tools in agricultural landscapes.

KEY WORDS: buffer zones, water protection, ecohydrology, biological filters, wetlands

Introduction

Due to rising levels of anthropogenic pollution in agricultural areas, there is a growing need for improvement in ecosystems' capacity, resistance to pollution and water quality (Sohel & Ullah 2012). Those goals can be achieved, inter alia by balancing hydrobiological processes in flora and fauna management plans. In line with ecohydrological principles, the creation of buffer zones in environments exposed to high levels of anthropogenic pressure is one of the most effective tools in controlling water pollution (Caracciolo *et al.* 2014). Knowledge of environmental biotechnology combined with hydrotechnical engineering solutions is required to control the levels of biogenic elements and to promote biodiversity by creating habitats for various species of plants and animals (Kędziora 2007, Sohel & Ullah 2012, Zalewski 2013). In areas that are at the greatest risk of diffuse source pollution, aquatic ecosystems can be

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managed by preserving or creating retention reservoirs, reclaiming land, creating wetlands, buffer zones with diverse vegetation and barriers that directly protect the banks of water bodies and watercourses (Ryszkowski *et al.* 1999, Sohel & Ullah 2012).

The concepts of buffer zones and biogeochemical barriers are often used interchangeably, and the criteria for distinguishing between them are not clearly identified in the literature (Izydorczyk *et al.* 2013, Sowiński *et al.* 2004, Wysocka-Czubaszek & Banaszuk 2003). In this review, biogeochemical barriers are regarded as an integral part of buffer systems. Solutions of this type can act as marginal filters situated directly in the littoral zone of an aquatic ecosystem, but the resulting biofiltration effects may be low if initial pollutant loads are high (Izydorczyk *et al.* 2013). The area of the buffer zone separating agricultural and urban areas from aquatic ecosystems has to be expanded, and diverse vegetation should be used to effectively prevent degradation of water bodies (Maksimenko *et al.* 2008, Ryszkowski 1999). Buffer zones separating aquatic and terrestrial ecosystems do not have to be static and passive barriers, and they can actively control the flow and transformation of matter and energy to create areas characterized by high levels of biodiversity (Miałdun & Ostrowski 2010).

The role of buffer zones in agricultural landscapes

Buffer zones limit the spread of pollutants or retain them in agricultural habitats (Koc & Szyperek 2004). A buffer zone is a strip of land maintained in permanent vegetation which separates agricultural land from watercourses and water bodies. Buffer zones provide effective physical, biological and chemical protection of water bodies against surface and subsurface contamination (Wasilewski 2012). They support vital processes such as assimilation of inorganic compounds, including nitrogen and phosphorus, by plants and their transformation to biomass, as well as biochemical processes that involve microbial biofilms. Soluble and insoluble phosphorus compounds are absorbed and transported from the surface to deeper soil layers (Błaszczyk 2010, Carluer 2011, Izydorczyk *et al.* 2013).

The effectiveness of natural and artificial barriers should be evaluated in view of various factors. Pollutants are removed by plant and soil filtering mechanisms, therefore, the rate of surface runoffs and the width of the buffer strip should be optimized to increase pollutant and sediment retention (Blanco-Canqui & Lal 2008, Ławniczak & Zbierska 2007, Stachowicz & Nagengast 2013). The selection of plant species is a very important consideration. Tall plants promote the development of microbial biofilms on their aboveground parts, and well-developed root systems improve soil quality. The presence of plants in the buffer zone also stabilizes the shoreline, prevents erosion, reduces runoff rates and improves soil structure, which is of particular importance in terms of surface coverage of grasses (Blanco-Canqui & Lal 2008, Sahu & Gu 2009, Sohel & Ullah 2012). Buffer zones should be created with consideration for vegetation types, the habitat preferences of plants and their ability to adapt to various hydrological conditions. Native plants should be introduced to artificial buffer zones with the aim of enhancing the local landscape (Izydorczyk *et al.* 2013). The life span of plants and their ability to propagate, to form dense patches and to eliminate or neutralize pollutants flowing in the direction of water bodies should be evaluated. For buffer zones to effectively purify water, plant communities should have diverse species composition. They should comprise minimum nine plant species (Wasilewski 2012). According to estimates, buffer zones which have a mosaic pattern and incorporate various species of trees, shrubs and grasses are six times more effective in reducing phosphorus flows to water bodies than catchments characterized by homogeneous vegetation (Ryszkowski 1999). Higher levels of organic carbon are found in fields that feature clusters of trees than in intensively fertilized fields. The presence of trees increases the content of humic substances in the soil and contributes to soil porosity and retention capacity (Jaskulska & Hoppe-Wawrzyniak 2013).

The role of various buffer zones in reducing pollution levels in aquatic ecosystems

Buffer zones composed of grasses, sedges and herbaceous plants are highly effective in eliminating nitrogen compounds. According to estimates, a six-metres-wide buffer strip is capable of reducing total nitrogen concentrations by 47%, and this biogenic element is nearly completely eliminated when the width of the buffer zone is extended to 20 m (Wysocka-Czubaszek & Banaszuk 2003). A biogeochemical barrier significantly delays the transport of nitrogen to wetlands in river valleys. Nitrogen levels may be reduced by denitrification and absorption, but they tend to increase in buffer zones over time. The adverse consequences of this process may be minimized by river floods that take place every few years. Plants with shallow root systems may be unable to block the transport of nitrogen into deeper soil layers (Wysocka-Czubaszek & Banaszuk 2003). Nitrophilous plants can be introduced to man-made buffer zones to increase their nitrogen removal capacity. At the end of the growing season, grasses should be cut to reduce nitrogen levels which are very high in plant tissues during that period (Lemkowska *et al.* 2010). Plants of the family Fabaceae are able to form dense patches of vegetation, and they are characterized by a long life span and a long growing season during which nutrients are intensively assimilated for the needs of biomass production and propagation. Plants with a fibrous root system are firmly attached to soil particles, which increases their resistance to powerful surface runoffs (Wasilewski 2012).

The common reed (*Phragmites australis*) is highly capable of accumulating heavy metals, and it can significantly contribute to the effectiveness of biogeochemical barriers in water bodies. The species has low environmental requirements, and it is common in littoral zones. Research has demonstrated that the highest concentrations of heavy metals are found in the roots of reed plants. Lead concentrations were determined at 16.54 $mg \cdot kg^{-1}$ DM in roots, 9.87 $mg \cdot kg^{-1}$ DM in stems and 13.20 $mg \cdot kg^{-1}$ DM in leaves. Zinc levels reached 104.10 $mg \cdot kg^{-1}$ DM in roots and 28.40 $mg \cdot kg^{-1}$ DM in leaves (Bonanno & Giudice 2010). In ecosystems contaminated with metachlor, a popular pesticide, reed plants reduced contamination levels by 28% in comparison with sites where reeds were not present. Other plant species capable of lowering pesticide levels, *Leersia oryzoides* and *Typha latifolia,* reduced metachlor concentrations by 88% (Vymazal & Březinová 2015). In biogeochemical barriers in littoral zones, pesticides are adsorbed onto sediment particles. Soluble fractions of pesticides such as glyphosate, propiconazole and fenpropimorph were removed in 24–70%, 32–78% and 61–73%, respectively (Syversen & Bechmann 2004).

Riparian forests are highly valuable buffer zones which can significantly lower the loads of biogenic elements. They constitute transitional zones between agricultural land and aquatic ecosystems. According to estimates, a 5–30 m wide buffer zone can reduce pollutant runoffs by more than 30%. Species diversity also plays a crucial role in buffer zones, and it contributes to the removal of nitrogen and phosphorus compounds (Blanco-Canqui & Lal 2008, Fortier *et al.* 2015). Different types of buffer zones and their efficiency in removing biogenic elements are shown in Table 1. The presented data indicate that zones with diverse vegetation are most effective in minimizing pollution levels. The highest rates of nitrogen and phosphorus removal were noted in a buffer zone overgrown with trees, shrubs and grasses. The presence of tall trees with root systems that stretch several meters away from the littoral zone improves soil drainage (Fortier *et al.* 2015).

Table 1. Types of buffer zones and their ability to remove biogenic pollutants (Blanco-Canqui & Lal 2008).

Type of buffer zone	Width of buffer zone [m]	Efficiency of nitrogen removal [%]	Efficiency of phosphorus removal [%]
Deciduous forest	10	97	78
Deciduous trees and grasses	75	27	56
Trees, grasses, shrubs	16	94	91
Shrubs and weeds	18	32	30

The white cedar (*Thuja occidentalis*) accumulated 240 kg N·ha^{-1} in roots and 1050 kg N·ha^{-1} in aboveground parts. The species, initially a shrub, eventually develops into a tree, and its accumulation capacity increases with age (Fortier *et al.* 2015). Poplars are a common species of trees that store nitrogen in the form of protein. Poplars reduce biogenic pollution levels, create supportive habitats for forest animals, store nutrients and regulate hydrological conditions in flood zones. Their ability to accumulate carbon increases with age. Traditional buffer zones are being replaced with systems capable of producing biomass and accumulating significant amounts of biogenic elements: 29–107 t C·ha^{-1}, 29–141 kg P·ha^{-1} and 284–1120 kg N·ha^{-1} (Fortier *et al.* 2015).

The location of green belts that act as biogeochemical barriers is equally important. Nitrogen retention can be improved by designing an additional barrier in the middle of a buffer zone rather than directly in the littoral zone. A species that can be effectively used for that purpose is switchgrass (*Panicum virgatum*). A biogeochemical barrier in the littoral zone is capable of eliminating

60–80% of nitrates, and its removal capacity increases to 60–95% when it is located in the middle of the buffer zone (Sahu & Gu 2009).

Small retention reservoirs such as ponds can also act as biogeochemical barriers. Complex systems comprising a body of water, bottom sediments and littoral vegetation are highly effective in accumulating biogenic elements. Bottom sediments and shoreline plants absorb large amounts of pollutants and play a very important role in water purification systems. Pollutants flowing into a pond are filtered by meadow vegetation and rush plants (Koc & Szyperek 2004,

Zieliński & Jekatierynczuk - Rudczyk 2015). A belt of meadow vegetation increases nitrogen retention in the entire system, which is demonstrated by a high rate of accumulation per unit surface area (1.03 kg $N \cdot m^{-2}$). Bottom sediments are major retention reservoirs of biogenic elements. According to estimates, more than 95% of nitrogen is accumulated in bottom deposits in water bodies devoid of littoral vegetation (Koc & Szyperek 2004). Despite promising research results, ponds should not be regarded as the only effective biogeochemical barriers because they are relatively quickly degraded on account of their small size. Systems with well-developed littoral vegetation are capable of accumulating 1.4 to 344 kg of nitrogen per ha of catchment area (Koc & Szyperek 2004).

Pollutants can also be retained by naturally occurring geomorphological structures. Ground moraine depressions in the Masurian Lake District are natural filters that capture biogenic elements and accumulate organic matter. Due to a high content of macronutrients and micronutrients, high sorptive capacity and the presence of deposits in the form of loose and relatively narrow slates, ground moraine depressions can be classified as biogeochemical barriers. Their sorptive capacity also determines the rate at which pollutants are retained by acidic meadow soils in agricultural areas (Sowiński *et al.* 2004, Ryszkowski 1999).

Artificial mechanical barriers can enhance physical and biological processes in plant and soil systems. Barriers formed by sedimentary rocks effectively prevent the leaching of phosphorus compounds. According to estimates, a limestone and dolomite barrier with a width of 1.5 m and a depth of 1.5 m can reduce total phosphorus concentrations by 51.3–63.3% (Izydorczyk *et al*. 2013).

Regular liming treatments increase the concentrations of magnesium and calcium ions and pose a threat for aquatic ecosystems. Buffer zones can significantly lower the content of ions in runoffs, and they are capable of retaining 20–54% of calcium and 46–72% of magnesium. The highest retention is reported in the first 10–15 m of the buffer zone (Życzyńska-Bałoniak *et al*. 2005).

Conclusions

Despite differences in their form and structure, buffer zones play a very important role in protecting aquatic ecosystems against pollution. The results of the cited studies demonstrate that buffer zones effectively reduce pollution caused by pesticides, mineral fertilizers and heavy metals. Buffer zones should be preserved and expanded in agricultural areas. The presence of diverse plant species in buffer zones significantly increases their retention efficiency. Buffer zones with a mosaic structure contribute to environmental protection by creating new habitats and preserving biological diversity. Favorable conditions for the coexistence of various flora and fauna species should be created in ecotones to maximize their self-purification capacity and reduce the risk of ecosystem degradation.

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Streszczenie

Bariery biogeochemiczne stanowią obszary o potencjalnie dużej zdolności do ograniczania przedostawania się metali ciężkich, pestycydów oraz związków biogenicznych do środowiska wodnego. Zastosowanie rozwiązań ekohydrologicznych pozwala na regulację nadwyżki pierwiastków biogenicznych oraz przyczynia się do wzorstu bioróżnorodności, dzięki wytworzeniu siedlisk dla licznych gatunków roślin i zwierząt. W niniejszym opracowaniu włączono bariery biogeochemiczne w ogół układów buforowych. Rozwiązania tego typu mogą być traktowane, jako filtry marginalne umiejscowione bezpośrednio w strefie przybrzeżnej ekosystemu wodnego, co w przypadku wysokiego wstępnego obciążenia spływu powierzchniowego może okazać się nie wystarczające dla osiągnięcia dobrych efektów biofiltracji. Aby w sposób skuteczny przeciwdziałać degradacji ekosystemów wodnych na obszarach rolnicznych, konieczne jest zwiększenie powierzchni strefy oddzielającej je od wód oraz wykorzystanie zróżnicowanej roślinności. W obrębie stref buforowych wyróżnia się asymilację związków nieorganicznych, w tym azotu i fosforu przez rośliny, co umożliwia ich transformację w biomasę, a także procesy biogeochemiczne realizowane dzięki aktywności drobnoustrojów występujących w postaci biofilmów. Ponadto proces sorpcji i transportu rozpuszczalnych oraz nierozpuszczalnych związków fosforu realizowany jest w glebie, gdzie odpływ krąży w jej wierzchniej warstwie. Skuteczne działanie stref buforowych powinno obejmować preferencje siedlisk, określone rodzaje roślinności i ich tolerancję dla różnych warunków hydrologicznych. Przytoczone badania zwracają uwagę na konieczność zachowania zróżnicowanych gatunków w obrębie stref buforowych. Obecność na obszarze jednego siedliska zarówno drzew, krzewów i traw zapewnia ponad 90% efektywność w usuwaniu związków biogenicznych. Zapewnienie odpowiednich warunków dla współistnienia wielu organizmów w obrębie jednego ekotonu pozwala na skuteczne działanie procesów samooczyszczania i redukuje ryzyko degradacji ekosystemu.

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Ecological status assessment of lakes using macrophytes

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ABSTRACT

Harmonisation of the laws of the Member States regarding the protection of the environment is one of the tasks of the European Union. Poland joined EU in 2004 and took on various commitments for the improvement of water status. In particular, the Water Framework Directive was a major breakthrough in the assessment of aquatic ecosystems. For the classification of stratified and non-stratified lakes Ecological State Macrophyte Index (ESMI) has been used. In Poland, the method for assessing the ecological status of lakes based on macrophytes has been developed for routine water monitoring shortly after joining the European Union. This index is one of the biological elements in the assessment of ecological status. It considers the whole plant communities in the reservoir. The key factor that ESMI reacts to is anthropopressure, which manifests itself as eutrophication. However, it is crucial that the lakes are also subject to different pressures. In this situation, the ESMI rating becomes only an indicative method. The article describes the role, process of evaluation and the most common problems related to ESMI.

KEY WORDS: Water Framework Directive, water quality, ecological status, ESMI, lakes

Introduction

For years, environmental monitoring using macrophytes in Poland and Europe was not playing a significant role. Several countries, e.g. the Netherlands, Belgium, Denmark, Germany and Estonia researched vegetation lake ecosystems in their territories. However, these works were merely intended to present the perennial macrophytes changes using simple methods (Ciecierska & Dynowska 2013). Only the European Union Directive 2000/60/EC of 23 October 2000, also known as Water Framework Directive (WFD), turned out to be a milestone in the evaluation of water ecosystems.

In Poland, the method for assessing the ecological status of lakes based on macrophytes was developed for routine water monitoring in 2005–2006. In this process 156 Polish lakes larger than 1 ha were used, including 78 larger than 50

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ha.Water reservoirs have been grouped under the terms of the multiplicity of vegetation and abiotic parameters. Among them four groups of macrophyte lakes were distinguished: I - soft water lakes (lobelia), II - lakes with water rich in calcium (deep charales lakes), III - lakes with water rich in calcium (shallow charales lakes) as well as IV - lakes of łęczyńsko-włodawskie lakeland. A separate classification, assessed by the Ecological State Macrophyte Index, has been proposed for the second and third type, respectively stratified and non-stratified lakes. The macrophytes indication method proposed by Prof. Marian Rejewski was the basis of its study (Rejewski 1981). Unlike other indicators, ESMI does not include the same plant taxa, but syntaxon, or their communities. In hydrobotanics this difference, however, is of little importance, due to the fact that aquatic plants tend to create almost single-species communities, and therefore the degree of coverage of the plant community is close to the degree of coverage of its dominant species (Tomaszewicz 1979, Panek 2011).

The method of assessment of ecological status of lakes based on macrophytes

Ecological State Macrophyte Index includes vegetation studies carried out in the field with a preparatory phase, some involving the calculation of the macrophyte indicators and classification of lakes to the appropriate abiotic types. ESMI has a value from 0 (meaning bad ecological status) to 1 (reflecting high water quality). This index takes into account parameters such as phytocenotic variety, maximum phytocoenotic diversity, colonization index, phytolittoral surface calculated as the sum of the areas of all plant groups and the area of the lake.

Research should be carried out in July and the first half of August because of the growing season optimum, then water vegetation is most representative and observation results are void of significant abberations. Macrophyte assessment of lakes in the basic monitoring network is done once for each lake, while for the benchmark lakes it should be performed every three years, indicating the studies done in subsequent years on the same transects (Dz.U. nr 162, poz. 1008). Studies should be carried out by two inspectors.

The preparatory phase

In this phase the preparation for field research begins. Starting with the standard equipment used for field monitoring studies of lakes, such as a vessel, protective clothing or life jackets for both inspectors and, finally, specialist equipment. For the macrophyte study it is important to collect additional equipment, which includes a GPS device, an echo sounder, bathymetric and topographic maps, ropes and poles used to determine the length and width of the transect, hook for collecting underwater vegetation, a research protocol, a Secchi disk, as well as plastic bags with a line or dryers with tissue paper for collecting botanical taxa difficult to gather which require identification in a laboratory.

Before starting field studies, it is required to calculate the smallest possible number of transects, which is necessary for the macrophytes research and to determine their layout on bathymetric maps of the lake, taking into account representativeness and diversity of vegetation. Factors that should also be taken into account include morphometry and usage of coastal catchment of a reservoir, in order to arrange them relatively equally over the entire surface of the reservoir. The minimum number of transects depends on the surface of the lake and the shoreline development, but it cannot be less than six. The number of transects is a minimal value and reducing it is possible only in strictly justified cases, such as severe weather conditions, the lack of elodeids or when the calculated number of transects considerably exceeds 30 (Kolada & Ciecierska 2009). It is calculated using the Jensen's formula for the lakes with a surface smaller than 0.2 km² (Jensen 1977):

$$\mathrm{MLT} = \frac{\mathrm{L}}{\sqrt{\pi * \mathrm{P}}}$$

and larger than or equal to 0.2 km²:

$$\mathrm{MLT} = \left(\frac{\mathrm{T_{min}}}{2} + \frac{\mathrm{P} - \mathrm{P_{min}}}{\mathrm{P}} * \frac{\mathrm{L}}{\sqrt{\pi * \mathrm{P}}}\right)$$

where:
MLT - the least (total) number of transects;
L - the length of shoreline (km);
P - the lake surface area (km²);
P_{min} - the lower limit of the size of the lake in a particular size class (Tab. 1);
T_{min} - the smallest number of transects required for the lake in a particular size class.

Table 1. Classification of lake sizes indicating the minimum number of transects required for the lake in a particular size class (Ciecierska & Dynowska 2013).

Size class	P [km²]	T_{min}
I – II	< 0.20	2
III	0.20 – 0.39	2
IV	0.40 – 0.79	4
V	0.80 – 1.59	6
VI	1.60 – 3.19	8
VII	3.20 – 6.39	10
VIII	6.40 – 12.79	12
IX	12.80 – 25.59	14
X	25.60 – 51.19	16
XI	51.20 – 102.39	18

The investigation of macrophytes in the field

Investigation of macrophytes on a certain transect includes the designation of its area with a width of not less than 30 m and length which reflects the colonization zone, from the lake shore to a maximum depth of occurrence of vegetation. The percentage of plant coverage of the entire transect is estimated and all the occurring plant communities on the transect with the estimated percentage of the coverage in relation to the total area occupied by the plants is identified based on the seven stage Braun-Blanquet scale (Golub *et al.* 2006).

During the studies it is important to include all the environmental groups starting from reed bed proper and reed bed of sedge (helophytes), through plants with floating leaves (nympheids), vascular submerged plants (elodeids), Charetea (charophytes) and mosses. It is never allowed to miss the transect where there were no macrophytes, except for the situation described above, because it will disturb the final ESMI evaluation. It is also important to make additional observations of the type of the bottom or the inclination of the littoral.

Table 2. Loliolide and its derivatives in marine organisms.

Braun-Branquet scale	Percentage of communities in the total area occupied by plants	The average coverage [%]
5	100 – 75	86
4	75 – 50	61
3	50 – 25	34
2	25 – 5	15
1	5 – 1	3
+	1 – 0.1	0.5

Calculation of macrophyte indicator

To determine the final value of the ESMI index it is necessary to average the data collected in transects and identify individual indicators containing information on the qualitative and quantitative state of macrophytes.

One of the most important indicators is the phytocoenotic diversification (H), calculated from the Shannon-Weaver Index (Panek 2001), which takes the form:

$$H = \sum \frac{n_i}{N} * \ln \frac{n_i}{N}$$

where: H - phytocenotic diversification index;
ni - area of specific plant community in the percentage of the total phytolittoral area;
N - total area of phytolittoral (100%).

The maximum value of phytocenotic diversity is also calculated (H_{max}) (Ciecierska & Dynowska 2013), according to the formula:

$$H_{max} = \ln S$$

where: H_{max} - the theoretical maximum rate of phytocenotic diversity;
S - the number of communities forming phytolittoral.

The structural simplifications of vegetation under anthropopressure (J) are reflected by the rate of the actual phytocenotic diversity (H), the theoretically possible maximal diversity (H_{max}) (Pielou 1966), calculated from the formula:

$$J = \frac{H}{H_{max}}$$

As a quantitative benchmark of macrophytes applied settlement rate (Z), expressing area actually occupied by the macrophytes (phytolittoral surface) and the surface potentially available to them, considered as the area of littoral limited by isobath 2.5 m (lake area, where the water is shallower than 2.5 m). Settlement rate should be calculated as follows (Ciecierska & Dynowska 2013):

$$Z = \frac{N}{P - isob. 2.5}$$

where: Z – settlement rate;
N - total area of phytolittoral (ha);
P - the lake surface area (ha);
isob. 2.5 - area limited by isobath 2.5 (ha).

The quantitative and qualitative indicators described above, included in a single formula, are used to calculate the Ecological State Macrophyte Index, which takes the form (Kolada & Soszka 2004, Ciecierska 2008, Ciecierska & Kolada 2013):

$$ESMI = 1 - \exp\left[-\frac{H}{H_{max}} * Z * \exp\left(\frac{N}{P}\right)\right]$$

where: H - phytocenotic diversification index;
H_{max} - the theoretical maximum rate of phytocenotic diversity;
Z - settlement rate;
N - total area of phytolittoral (ha);
P - the lake surface area.

Interpretation of the results

Until now ESMI index limit values have been determined only for stratified and non-stratified lakes with calcium-rich waters (Tab. 3).

Table 3. ESMI values defining water quality class according to the guidelines of the Minister of Environment of 2011

Ecological State*	Ordinanceof the Minister of Environment	
	Lower limit for ESMI values forstratified lakes	Lower limit for ESMI values for non-stratified lakes
High	0.68	0.68
Good	0.34	0.27
Moderate	0.17	0.11
Poor	0.09	0.05
Bad	<0.09	<0.05

*According tothe ordinanceof the Minister of Environment Journal of Laws of 2008. No. 162, pos. 1008

Classification of surface water according to the Ecological State Macrophyte Index is based on the biological indicator. It depends on many environmental and anthropogenic factors. That does not always facilitate interpretation of the data (Kłosowski & Kłosowski 2007). Therefore, during assessing the ecological status of lakes, next to biological elements such as phyto-plankton, phytobenthos, ichthyofauna, benthic macroinvertebrates and macrophytes, it is important to take into account the elements verifying the former (physicochemical), and, in the case of lakes, hydromorphological features (Soszka 2007, Kolada 2008). So:

- if the ESMI index value indicates good condition, but the participation of Charetea in phytolittoral is higher than 25% and higher than 3% in the Braun-Blanquet scale (in accordance with the agreed reference conditions), it is reasonable to increase the class by one level, that is, to a high water quality;

- when there is a situation that the value of the ESMI index indicates a state high or good, but more than 75% of phytolittoral take phytocenoses of invasive species such as *Ceratophyllum demersum* or *Elodea canadensis*, it is reasonable to decrease the class by one level.

- if in the lake there are no submerged plants at all but only a well-developed reed, then regardless of the value of the ESMI index the lake should be classified to bad ecological status;

- if the value of the ESMI index indicates a poor or bad water status, and/or there are almost no macrophytes in the lake, but the physico-chemical parameters indicate a higher status of water quality and there is no identified pressure of anthropogenic origin in the catchment, it is time to acknowledge that macrophytes are inappropriate to assess the ecological status of the water ecosystem.

- a similar problem may also be noted in lakes where lake basin has extremely steep slopes (Kolada & Ciecierska 2009, Ciecierska & Dynowska 2013).

Conclusions

Individual indicators included in the Ecological State Macrophyte Index containing taxonomic composition and abundance of macrophytes as well as composite index clearly and directly react to anthropopressure, considered as its main but not the only sign is the process of eutrophication.

To assess the ecological status of lakes which are subjected to pressures other than accelerated eutrophication, ESMI method should not be used, because it is not sensitive to these pressures. Prof. Hanna Ciecierska claims that a similar problem, as, concerns lakes with the shape of the bottom which has an adverse impact on the expansion of macrophytes. Therefore the ESMI evaluation should be treated only as an estimate with the assumption that it can be changed, for example, after the conclusion of the conversion to the ESMI formula amendments involving lake basin shape.

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Streszczenie

W Polsce metoda oceny stanu ekologicznego jezior na podstawie makrofitów opracowana została na potrzeby rutynowego monitoringu wód w latach 2005–2006 na zlecenie ówczesnego Ministra Środowiska. Do procesu tego posłużyło 156 jezior. Zbiorniki zostały pogrupowane pod względem różnorodności roślinności oraz parametrów abiotycznych. Wśród nich wyodrębniono cztery grupy jezior makrofitowych: I – jeziora o wodach miękkich (lobeliowe), II – jeziora o wodach bogatych w wapń (ramienicowe głębokie), III – jeziora o wodach bogatych w wapń (ramienicowe płytkie), a także IV – jeziora łęczyńsko-włodawskie. Dla drugiego oraz trzeciego typu, odpowiednio jezior stratyfikowanych i niestratyfikowanych zaproponowano odrębną klasyfikację ocenianą za pomocą Makrofitowego Indeksu Stanu Ekologicznego. Podstawą jego opracowania była metoda makrofitoindykacji roślinności jezior rejonu Laski w Borach Tucholskich zaproponowana przez profesora Mariana Rejewskiego w latach 70. XX w, a udoskonalona w następnych latach przez profesor Hannę Ciecierską. Określała ona bioróżnorodność na poziomie zbiorowisk roślinnych fitolitoralu tworzonych przez makrofity.

Metoda ESMI obejmuje zarówno badania roślinności przeprowadzone w terenie z etapem przygotowawczym oraz część polegającą na wyliczaniu samych wskaźników makrofitowych. Indeks przyjmuje wartości od 0, obrazującego zły stan ekologiczny, do 1 odzwierciedlającego stan bardzo dobry. W trakcie wyliczania końcowego indeksu ESMI uwzględnia się parametry takie jak: różnorodność fitocenotyczna, maksymalna różnorodność fitocenotyczna, indeks kolonizacyjny, powierzchnia fitolitoralu obliczona jako suma powierzchni wszystkich zespołów roślinnych oraz powierzchnia samego jeziora.

Zarówno poszczególne wskaźniki wchodzące w skład ESMI uwzględniające skład taksonomiczny oraz obfitość makrofitów, jak i sam zespolony indeks, wyraźnie i w sposób kierunkowy reagują na antropopresję. Jako jej główny, ale nie jedyny przejaw przyjęto proces eutrofizacji, dlatego otrzymane wyniki klasyfikacji porównywano różnymi wskaźnikami trofii. Zatem, do oceny stanu ekologicznego jezior podlegających presjom innego typu niż przyśpieszona eutrofizacja, metoda ESMI nie powinna być wykorzystywana, ponieważ nie jest ona podatna na te presje. Podobny problem, jak zauważa profesor Hanna Ciecierska dotyczy jezior o niekorzystnym dla rozwoju makrofitów ukształtowaniu dna zbiornika. W związku z tym powinno potraktować się ocenę ESMI jako szacunkową z założeniem, iż może ona ulec zmianie, np. po zawarciu przeliczenia do wzoru ESMI poprawki na ukształtowanie misy jeziornej.

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Plants on duty – phytotechnologies and phytoremediation at a glance

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ABSTRACT

Phytotechnologies are plant based technologies of remediation and containment of pollutions. Many advantages of phytotechnologies such as control of water and biogeochemical cycles, positive impact on soil characteristics and lowering the risk of erosion, contaminant immobilization and destruction, habitat restoration, low costs of implementation, and high public acceptance, decide that in more and more cases it is a preferred and recommended method of rehabilitation. Vegetation selected to the particular site conditions and having required characteristics will shape other biotic communities. It is thus immensely important to gather detailed knowledge about all the elements and processes occurring at the place of interest, before employing adequate phytotechnology application.

KEY WORDS: ecotechnologies, rehabilitation, remediation, watershed management, pollution control

Introduction

As the degradation of ecosystems progress scientists and engineers look for more advanced and sophisticated techniques for protection, remediation, and restoration. These techniques are often very expensive and the results are not as pronounced as one would like them to be. From this disappointment a new approach emerged, the one that turns away from single specialized solutions to multi-disciplinary and integrated methods. Most environmental problems derive from lack of understanding of ecosystem functioning. Solutions based on this insufficient knowledge are short-sighted and often harmful. Holistic approach, broad understanding of all the elements and processes operating in nature, sociological aspects and economical constrains, integrates numerous problems, but shows broad perspective for successful solutions (IETC 2003).

Plants, as primary producers, are the base of terrestrial and many aquatic ecosystems. Their abundance and species composition play vital role in energy flow (mainly through photosynthesis) (Danilov-Danil'yan *et al.* 2009), as well as elements and water cycles. However, with the human development and urban spread, especially visible in the previous

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century, plant cover noticeably declined. The results of this reduction affected humans well-being, as provided ecosystem services also decreased (Assessment 2005). Thus it seems crucial to reestablish vegetation cover in places where it was severely damaged or deliberately removed to satisfy short-sighted needs. In the last century the amount of inorganic and organic contaminants (especially synthetic substances) rose dramatically degrading many ecosystems. In that case creation of artificial buffering zones and constructed wetlands may counterbalance negative effects of pollution *et al.* 2010).

Ecotechnologies rely on immanent ability of ecosystems to flexibly respond to disturbances, even man-made (IETC 2003). In that context vegetation can be used to strengthen carrying capacity, through water filtration, control of biochemical cycles, as well as habitat creation and biodiversity increase. Plants also have an aesthetic value for humans, and thus are welcome by society as a solution to environmental problems.

What are phytotechnologies?

As its name suggests phytotechnologies are plant based technologies. The UNEP states that by engaging ecological engineering principles phytotechnologies are ecotechnologies, using an integrative approach. They are used to solve environmental problems such as degradation and rehabilitation of already degraded ecosystems, as well as control of environmental processes in the watershed (IETC 2003). They are used to protect and remediate soil, sediments, surface water and groundwater. Of course different aims and objectives require appropriate phytotechnology application but the essential mechanisms remain the same. Those mechanisms which facilitate nutrient and pollutant degradation, removal and sequestrations originate from natural physiological processes occurring in plants or in rhizosphere. Because those mechanisms are natural and because plants are commonly available the costs of using phytotechnologies are relatively low when compared to traditional solutions (Technology and Team 2009, Vaněk *et al.* 2010).

Advantages of phytotechnologies

Being at the bottom of a trophic chain vegetation plays vital role in energy flow and organic matter distribution. It controls water cycle and biogeochemical cycles, not only locally but regionally and globall as well (Zalewski 2002). Advantages of phytotechnologies are directly linked to high biomass of vegetation. The benefits of maintaining high plant biomass include:

1. Water retention and infiltration control, as plants are capable of intercepting and evaporating rainwater – limiting the infiltration, up-taking and transpiring water from the different soil levels (as well as groundwater), and minimizing runoff. Water control is also important from the point of view of catastrophic events. Vegetation limits the possibility of serious floods and droughts (van Beukering *et al*. 2003, Whetton *et al.* 1993)
2. Stabilization of temperature and heat budget. By releasing water through evapotranspiration process plants cool themselves and the surroundings. Vast

amount of trees or other plants can visibly alter the water vapor concentration which causes cloud cover and precipitation (Budyko 1986). Even agricultural plants show positive impact reducing range of extreme temperatures (Ryszkowski 1998).

3. Change in soil characteristics. Via roots plants release phytochemicals such as sugars, amino acids, enzymes, proteins, etc. Those substances, called rhizodeposits, are a carbon source for soil microbes, thus making their proliferation up to four times greater than in sites without vegetation (Philippot *et al.* 2013; Technology and Team 2009). Some of the secondary metabolites are involved in establishing symbiotic relationships or in deterring pathogens and pests. Soil pH (in the vicinity of the plants) can change up to two units depending on the ions uptake. Soil oxygen pressure is affected by water uptake as well as root respiration – oxygen release (Philippot *et al.* 2013). With water plants also uptake dissolved inorganic nutrients thus changing their concentration is soil. This process is sometimes enhanced by microbial activity.

4. Minimizing erosion rates. As roots penetrate the soil they stabilize it and make it less vulnerable to water- and wind-induced erosion (Kirkby 1995). Soil migration can be a problem also with regard to pollution spread. If the soil is contaminated leaching will lead to pollution dispersal (nonpoint source) (Technology and Team 2009).

5. Mitigating transfer of nutrients and pollutants from terrestrial to aquatic ecosystems. Aquatic ecosystems like oceans and seas, lakes, ponds and rivers are sinks for carbon, nitrogen and many contaminants. Vegetation has the capacity of reducing the amount of biogenic compounds and harmful substances flowing to those ecosystems though water control and nutrient uptake.

6. By sequestering carbon and nitrogen in vegetation it is possible to balance global climate patterns (Zalewski & Wagner-Lotkowska 2004). The above-mentioned stabilization of temperature is yet another example of plants positive influence on climate.

7. Providing habitat and enhancing biodiversity. In most of phytotechnology projects habitat restoration is a by-product but it is not less important. Creation of wetlands, for example, mainly purifies the water but also provides habitat for fish and other animals (Grayson *et al.* 1999). Furthermore increased diversity of animals can diminish the impact of pests on vegetation, both wild and agricultural (Zalewski & Wagner-Lotkowska 2004).

8. New source of bioenergy. Some plants can be used as a source of energy, because they grow fast and produce a lot of biomass. One of the best known examples are poplars and willows. Kept in a short rotation coppice they produce enough biomass to make their plantations profitable (Marmiroli *et al.* 2006). Mixed coppice systems, consisting of trees and arable crops or grasses, offer not only a stable source of biofuel but also higher biodiversity and habitat stability than monocultures (Costanzo & Bàrberi 2014). From agricultural waste biogas can be produced and also used as a source of energy (Ehret *et al.* 2015).

9. Increased value of land. The more services are provided by certain land patch the higher is its value. All above-mentioned advantages result in larger range of provided ecosystem services thus creating attractive and desirable areas (Assessment 2005). Land degradation results in lower productivity, which in turn lowers land value and market price. Therefore protection and

reestablishment of vegetation cover will increase it (Sinden & King 1996).

10. Possibility of restoration and rehabilitation of degraded site. Using plants as an instrument of remediation is widely applied. Phytotechnologies considered as eco-friendly technology, offer in situ treatment of contaminated media as well as many positive side-effects including, but not limited to, all the benefits of maintaining high plant biomass.

11. A sense of well-being. In light of ecosystem services vegetation is a key element responsible for human well-being. All the provisioning and supporting services are directly linked to the state of plant cover. Most of the regulating services and some of the cultural services also depend on florae abundance, composition, and diversity (Assessment 2005).

Using phytotechnologies is also beneficial in terms of cost-effectiveness. Compared to traditional methods of remediation, which often require energy-consuming equipment and advanced reagents, phytoremediation offers solar driven and relatively simple techniques. The costs of using phytotechnologies is around 10–20% of the mechanical treatment costs (Vaněk *et al.* 2010). There is also high public acceptance for plant based technologies as they provide wide range of environmental benefits and the possibility of adverse effects on ecosystems is minimal (Thangavel & Sridevi 2014).

How to choose adequate phytotechnology?

Before starting any rehabilitation project it is very important to gather information regarding all the elements and processes occurring in the particular ecosystem or watershed. The more detailed and thorough the knowledge is the better solution can be applied. In the planning phase it is also important to set measurable goals as to be able to evaluate the success. Pre-defined objectives, goals, targets and metrics allow to calculate how well selected solution works at any time during the project operation (DuBowy 2013). It is also important for making adjustments to the rehabilitation plan and optimization of the system – adaptive management (Zalewski 2011).

According to Phytotechnology Technical and Regulatory Guidance and Decision Trees (Technology and Team 2009) most commonly applied phytotechnologies include: phytostabilization covers, riparian buffers, ponds, lagoons and basins, tree hydraulic barriers phytoremediation groundcovers, phytoremediation tree stands and constructed treatment wetlands.

- *Phytostabilization covers* are used on impacted soil and sediments to stabilize it, prevent erosion and contaminant dispersal associated with it. Plants extract the contaminant and sequester it in their tissues. Vegetation covers can also be used to prevent infiltration and protect clean surface water. In that case plants limit the infiltration and surface runoff, minimizing the risk of contamination spread.
- *Tree hydraulic barriers* can effectively contain contaminant present in groundwater. To reduce movement of impacted groundwater actively tapping it trees both extract and transpire water, and sequester pollution. Also clean groundwater can be protected against lateral migration of contaminants based on evapotranspiration.
- *Phytoremediation groundcovers* and *phytoremediation tree stands* use degradation processes occurring in plants

and in rhizosphere. Groundcovers break down contaminants present in soils and sediments, while tree stands target contaminants in groundwater.

- *Riparian buffers* are among the most universal applications, since they can limit the pollution spread to protect surface water (also by erosion control), but are phytoremediation application as well. The media which buffers protect are: impacted surface water, clean and impacted groundwater. The remediated media may include surface and groundwater.
- *Ponds, lagoons and basins* are small reservoirs which prevent the spread of contaminated water or remediate impacted surface water. In the first case stagnating water is used by plants (extraction, transpiration, sequestration) and it evaporates and infiltrates. Remediated media can include waste water.
- *Constructed treatment wetlands* are wide-spread techniques of remediating surface water. Macrophytes metabolize contaminants and provide oxygen for aerobic degradation of organic matter and nitrification.

Selecting suitable plants for chosen application is also very important. Plants must not only have satisfying accumulation capacity but they also have to blend into rehabilitated habitat. It is absolutely unacceptable to use non-native and invasive species, regardless of their beneficial role in their natural habitats. A screening process should start with identification of species already existing on site. If those species have remediation potential (appear in the phytotechnology databases) it is recommended to use those plants. If not, it is necessary to look for the suitable species in the databases or scientific journals. In some cases that might not be enough and one would have to look for hybrids or related species. If that option also fails GMO species should be taken into consideration. When the use of plants is impossible, as they would not survive certain contamination levels, phytotechnologies cannot be used and other approaches ought to be considered.

Conclusion

Many possible applications of phytotechnologies result in growing interest in this type of environmental solutions. Other advantages linked to high plant biomass make the use of phytotechnologies even more tempting. But there are also some limitations one have to keep in mind. Not always plants can survive high contamination levels. Climate conditions and seasonal changes can interfere with vegetation growth. A large surface area is often required to achieve certain cleanup goals. And last but not least, phytotechnologies and phytoremediations are fairly new practices and the knowledge concerning themis still limited.

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Streszczenie

W świetle postępującej degradacji środowiska naukowcy i inżynierowie szukają coraz bardziej zaawansowanych metod pozwalających na ochronę, remediację i rekultywację ekosystemów. Obecnie preferowane są rozwiązania holistycznie, biorące pod uwagę nie tylko aspekty środowiskowe, ale również ekonomiczne i społeczne.

Fitotechnologie to metody remediacji i zatrzymywania zanieczyszczeń oparte o wykorzystanie roślin, procesów zachodzących w ich tkankach oraz w ryzosferze. Zwiększanie pokrywy roślinnej powiększa pojemność środowiska poprzez filtrację wody, kontrolę cykli biogeochemicznych, a także tworzenie siedlisk i zwiększanie bioróżnorodności. Rośliny mają też pewną wartość estetyczną, dlatego ich wykorzystanie w celu rozwiązywania problemów środowiskowych jest mile widziane przez społeczeństwo. Wśród zalet fitotechnologii należy również wymienić ich koszt, który szacunkowo jest około 10-20% niższy niż analogicznej skuteczności rozwiązanie tradycyjne (Vaněk i inni 2010).

Dobór odpowiedniego rozwiązania podyktowany jest celem przedsięwzięcia. Najczęściej wykorzystywane rozwiązania zatrzymujące zanieczyszczenia to stabilizujące pokrywy roślinne i drzewne bariery hydrauliczne. Rozwiązania mające na

celu zniszczenie zanieczyszczenia to pokrywy i drzewostany fitoremediacyjne. Część rozwiązań ma potencjał remediacyjny, ale także zatrzymuje zanieczyszczenia, to m.in.: strefy buforowe, adaptowane zbiorniki małej retencji oraz oczyszczalnie hydrofitowe.

Wykorzystanie fitotechnologii ograniczone jest stężeniami zanieczyszczeń, których rośliny mogą nie przetrwać oraz warunkami klimatycznymi i sezonowymi, a także koniecznością poświęcenia dużego obszaru pod uprawę. Ponadto zabiegi wykorzystujące rośliny są stosunkowo nowymi rozwiązaniami i jeszcze nie wszystko wiadomo o ich możliwościach i konsekwencjach użycia.