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Review

Opportunistic Macroalgae as a Component in Assessment of Eutrophication

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Abstract: For the last few decades, coastal eutrophication with the associated mass development of opportunistic macroalgae has increased on a global scale. Since the end of the 2000's, the number of studies of macroalgal blooms also increased many times. Mass occurrences of such species as *Cladophora* spp., *Ulva* spp., and *Spirogyra* spp. caused a necessity to improve existing methods of ecological assessment and develop new ones. There are many indices based on macroalgae and developed for marine and estuarine ecosystems. However, for correct evaluation, they demand a presence of a number of species, including perennial species from the order Fucales. This requirement cannot be satisfied in fresh or brackish waters, including some estuaries, because often, the freshwater communities are dominated by only one or two opportunistic species. The present paper defines the most relevant topics in studies of macroalgal blooms and reviews indices and metrics which can be recommended for the ecological assessment in diverse habitats influenced or dominated by opportunistic macroalgae species. For ecological assessment of opportunistic communities, according to their seasonal peculiarities, the author recommends, besides biomass, involving evaluation of algal mats (thickness, coverage) and signs of hypoxia.

Keywords: coastal eutrophication; *Cladophora*; *Spirogyra*; algal mats; ecological assessment; opportunistic macroalgae; green tides

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1. Introduction

Coastal ecosystems are characterized by high diversity and vulnerability [1], and macroalgae play a key role in their productivity and food webs [2]. The increase in nutrient loading and pollution during the last century has caused changes in many aquatic communities. In coastal ecosystems, it led to the re-building of the food webs, massive blooms of opportunistic macroalgae, and changes in species composition [3]. During the last few decades, mass occurrences of macroalgae have been registered around the world and were called "green" and "golden" tides [4]. The majority of opportunistic species, which form macroalgal "blooms", belong to phylum Chlorophyta (genera *Cladophora* Kutz, *Ulva* L.) and Ochrophyta (genera *Pylaiella* Bory de Saint-Vincent, *Ectocarpus* Lyngbye, *Sphacelaria* Lyngbye) [4]. The term "green tide" is usually applied to marine and estuarine ecosystems; however, this event also occurs in freshwater habitats. In freshwater ecosystems, the most famous of those are massive occurrences of *Cladophora glomerata* (L.) Kutz. in American Great Lakes [5] and "blooms" of *Spirogyra* spp. (Zygnematophyceae, Charophyta) in Lake Baikal [6]. Changes in the structure and biomass of the coastal communities caused a necessity to create tools for environmental assessment, which would focus on opportunistic species of macroalgae. According to the Water Framework Directive (WFD) of the European Union (Directive 2000/60/EC) [7] and the EU Marine Strategy Framework Directive (MSFD, Directive 2008/56/EC) [8], aquatic macrophytes, including macroalgae, are listed as the biological quality elements (BQEs) for environmental assessment of the coastal waters. Nowadays there are many methods and indices for evaluation of the ecological status, which are based on macroalgae [9]. The majority of them are adapted to marine and estuarine ecosystems with a number of macroalgal species. However, freshwater habitats usually have only one or few dominant species of macroalgae [10] and need to have their own criteria for ecological assessment. In turn, marine and estuarine ecosystems impacted by eutrophication also require the application of updated methods of assessment.

Since macroalgae have the ability to accumulate pollutants (e.g., trace metals), they can be used for an ecological assessment as indicators of both: eutrophication and pollution [11,12]. At the present time, both directions are developing and have their own limitations. The goal of this paper is to review the most relevant parameters and methods for the ecological assessment based on opportunistic macroalgae. The indices reviewed in the paper had been designed with involvement of opportunistic species of macroalgae as the metric.

2. Material and Methods

The search of the literature was performed in the Scopus database with a limit of the year 2022 and use of keywords: "green" AND "tides", "ecological" AND "assessment", "macroalgae", "algal" AND "mats", "Spirogyra", "Cladophora", "Cladophora" AND "blooms", "macroalgae" AND "index", "opportunistic AND macroalgae". The results of the search were filtered with options "area of knowledge" and "key words". After automatic filtration, the lists were checked manually and cleaned from irrelevant papers. Finally, four lists were saved: (i) the list "Green tides" included papers on "green tide" events in the marine and estuarine ecosystems, with the majority of papers focused on aspects of *Ulva* spp. blooms; (ii) the list "Cladophora" included papers on the mass development of *Cladophora* spp.; (iii) the list "Spirogyra" included papers on *Spirogyra* spp. blooms; (iv) the list "Ecological assessment with macroalgae" included papers on the different aspects of the ecological assessment and macroalgal indices.

3. Results

3.1. Green Tides Studies

The list "Green tides" included 402 papers for the time period from 1978 (the first mention of the term) to 2022. The first paper in 1978 reported on the mass bloom of *Cladophora prolifera* in Bermuda, which started in the 1960s [13]. The authors also measured the primary production of these algae and made a proposition that elevated levels of nutrients could be a possible reason for blooms [14]. In 1981 W. Schramm and W. Booth showed that elevated phosphate concentrations didn't increase the primary production of *C. prolifera*. However, even in oligotrophic conditions, these algae were able to accumulate a surplus of phosphorus [15]. Later, in 1989, it was shown that the mass development of these algae was driven by groundwater nutrient supply together with efficient utilization and recycling of dissolved organo-phosphorus compounds [16].

Mats of *Ulva* spp. (recorded as *Enteromorpha clathrata*) were reported for Richardson Bay, a small embayment in north San Francisco Bay, in 1982 in the study on the relationship between photosynthetic activity and main environmental conditions (light, temperature, and salinity) [17]. At the same time, blooms of *Ulva* spp. and the influence of algal mats on benthic fauna were studied in Langstone Harbour, England [18,19] and continued on the western coast of the UK [20]. Since the 1990s, green tides have been reported in different sites around the world [21,22]

Till the beginning of the 2000s, the number of published works hadn't exceeded 2 per year. However, in 2010 the number of published papers increased sharply, which can be related to the first massive outbreak of *Ulva* spp. population in 2008 in the Yellow Sea [23]. When starting from 2014 and to present time, the number of papers increased and achieved a few dozen per year (Figure 1).

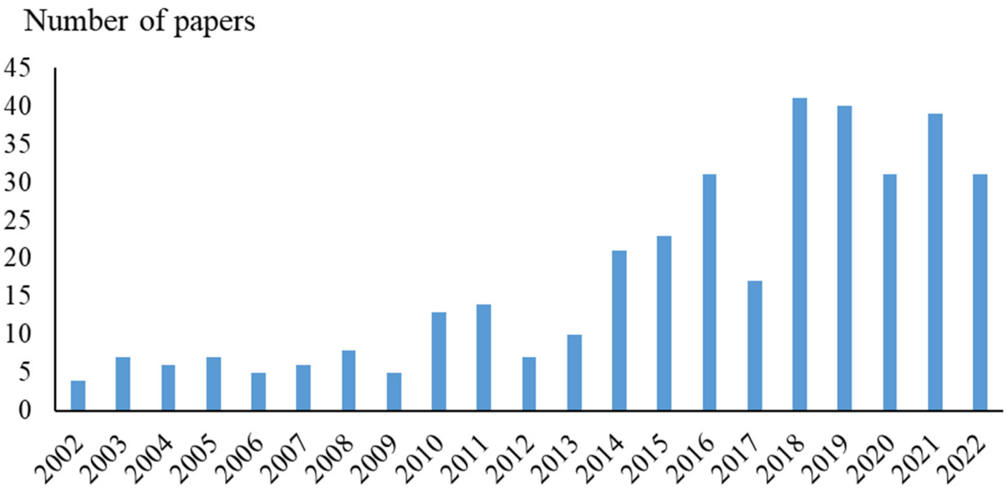

Figure 1. The number of published papers on the topic "Green tides" for the last 20 years.

Together with an increase in the number of papers, the leadership among the countries on this topic also changed, and from 2011–2022, China took a leading position (Figure 2).

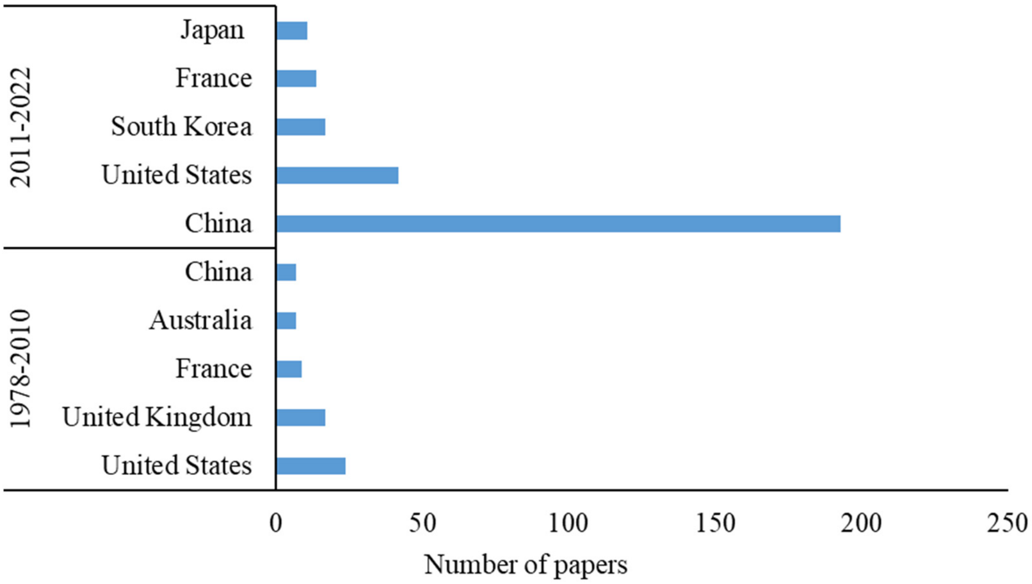

Figure 2. Countries with the highest number of published papers on the "Green tides" topic in two time periods.

Analysis of the most cited papers (Table 1) has shown that the most relevant topics in the studies of opportunistic macroalgae blooms are (i) massive *Ulva* spp. blooms in marine ecosystems (mostly in the Yellow Sea and East China Sea) [23] and their dynamics and hidden mechanisms [24–26], (ii) *Cladophora* spp. mass development and biomass [27], (iii) Relationships between green tide algae and invertebrate community [28] and (iv) Growth and development of green tide algae under variable environmental and experimental conditions [29].

Table 1. Ten of the most cited papers on the topic "Green tides".

Paper	Number of Citations
Liu D. et al. World's largest macroalgal bloom caused by expansion of seaweed aquaculture in China. *Mar Pollut Bull.* 2009, *58*(*6*), 888–895.	417
Ye N. et al. 'Green tides' are overwhelming the coastline of our blue planet: Taking the world's largest example. *Ecol Res.* 2011, *26*(*3*), 477–485.	278
Watson SB. et al. The re-eutrophication of Lake Erie: Harmful algal blooms and hypoxia. *Harmful Algae*. 2016, *56*, 44–66.	265
Hu C. et al. On the recurrent *Ulva prolifera* blooms in the Yellow Sea and East China Sea. *J Geophys Res C Oceans.* 2010, *115*(*5*)	248
Liu D. et al. Recurrence of the world's largest green-tide in 2009 in Yellow Sea, China: *Porphyra yezoensis* aquaculture rafts confirmed as nursery for macroalgal blooms. *Mar Pollut Bull.* 2010, *60*(*9*), 1423–1432.	217
Taylor R et al. Preliminary studies on the growth of selected 'green tide' algae in laboratory culture: Effects of irradiance, temperature, salinity and nutrients on growth rate. *Bot Mar.* 2001, *44*(*4*), 327–336.	209
Keesing JK et al. Inter- and intra-annual patterns of *Ulva prolifera* green tides in the Yellow Sea during 2007–2009, their origin and relationship to the expansion of coastal seaweed aquaculture in China. *Mar Pollut Bull.* 2011, *62*(*6*), 1169–1182.	206
Norkko J et al. Drifting algal mats as an alternative habitat for benthic invertebrates: Species specific response to a transient resource. *J Exp Mar Biol Ecol.* 2000, *248*(*1*), 79–104.	171
Higgins SN. et al. An ecological review of *Cladophora glomerata* (Chlorophyta) in the Laurentian Great Lakes. *J Phycol.* 2008, *44*(*4*), 839–854.	170
Wang Z. et al. Who made the world's largest green tide in China?—an integrated study on the initiation and early development of the green tide in yellow sea. *Limnol Oceanogr.* 2015, *60*(*4*), 1105–1117.	150

3.2. Cladophora spp. Studies in the Context of the Green Tides

Since the papers on green tides are mostly focused on *Ulva* spp. blooms, additional search was performed for more *Cladophora* spp. studies. Initially, the search for the keyword "Cladophora" showed more than one thousand papers. After filtration and manual checking, with an exclusion of papers on taxonomy, molecular and genetic studies, physiology and biochemistry, chemistry, and engineering, only 57 papers were left on the list. In 1978–2007 the number of papers published every year was 0–2, but in 2008 there was a sharp rise in published works (8 papers). This rise is related to the re-eutrophication of the American Great Lakes and the start of active studies in the Baltic Sea. In 2008–2022 total number of papers on *Cladophora* spp. in the "green tides" context reached 40 versus only 17 papers in the previous period. According to a number of published works, the first five countries were arranged in the following order: (i) the United States (20 papers), (ii) Canada (11 papers), (iii) Russian Federation (8 papers), (iv) China (6 papers), (v) Australia (4 papers). The most cited papers are given in Table 2.

According to the most cited papers there can be concluded that the most popular topics are (i) Eutrophication of American Great lakes and freshwater ecosystems [5,27], (ii) Growth and development of *Cladophora* spp. under variable environmental and experimental conditions [16,29], (iii) Dynamics and changes in estuaries under eutrophication [30].

Table 2. Five of the most citing papers on *Cladophora* spp. in the context of green tides.

Paper	Number of Citations
Watson SB., et al. The re-eutrophication of Lake Erie: Harmful algal blooms and hypoxia. *Harmful Algae*, 2016, *56*, 44–66.	265
Taylor R., et al. Preliminary studies on the growth of selected "green tide" algae in laboratory culture: Effects of irradiance, temperature, salinity and nutrients on growth rate. *Bot Mar*, 2001, *44*(*4*), 327–336.	209
Higgins SN. et al. An ecological review of *Cladophora glomerata* (Chlorophyta) in the Laurentian Great Lakes. *J Phycol*. 2008, *44*(*4*), 839–854.	170
Lapointe BE, O'Connell J. Nutrient-enhanced growth of *Cladophora prolifera* in Harrington sound, Bermuda: Eutrophication of a confined, phosphorus-limited marine ecosystem. *Estuar Coast Shelf Sci*. 1989, *28*(*4*), 347–360.	144
Lavery PS., et al. Changes in the biomass and species composition of macroalgae in a eutrophic estuary. *Estuar Coast Shelf Sci*. 1991, *33*(*1*), 1–22.	114

3.3. *Spirogyra spp. Studies in the Context of Eutrophication*

Initially, a search on the "Spirogyra" topic showed 978 papers, and the majority of them were on Taxonomy and Systematics, Molecular and genetic studies, Engineering and applied sciences, etc. After automatic and manual filtration, 33 papers were extracted. The first mention of *Spirogyra* spp. bloom is dated to 1968 and was recorded in Lake Tahoe in 1967 [31]. In the following years, till 1998, in the Scopus database, there were no registered papers on *Spirogyra* spp. blooms. The next paper was published only in 1998 and reported on mats of *Spirogyra* spp. in Lake Biwa [32]. From the beginning of the 2000s, some papers about *Spirogyra* spp. blooms have been published regularly. In Saginaw Bay of Lake Huron, the mass development of these algae was reported in 2002 [33]. Since 2002 episodic occurrences of *Spirogyra* spp. blooms have been registered in different places of the world, and finally, the regular every-year blooms were recorded in Lake Baikal [6]. According to the number of papers on *Spirogyra* spp. blooms, five countries with the majority of papers were arranged in the following order: (i) Russian Federation (10 papers), (ii) United States (5 papers), (iii) Japan (3 papers), (iv) China and Poland (3 papers everyone). The most cited papers on this topic are given in Table 3.

Table 3. Five of the most cited papers on the topic of "*Spirogyra* spp. blooms".

Paper	Number of Citations
Kravtsova LS et al. Nearshore benthic blooms of filamentous green algae in Lake Baikal. *J Great Lakes Res*. 2014, *40*(*2*), 441–448.	89
Timoshkin OA et al. Groundwater contamination by sewage causes benthic algal outbreaks in the littoral zone of Lake Baikal (East Siberia). *J Great Lakes Res*. 2018, *44*(*2*), 230–244.	53
Pillsbury RW et al. Changes in the benthic algal community and nutrient limitation in Saginaw Bay, Lake Huron, during the invasion of the zebra mussel (*Dreissena polymorpha*). *J North Am Benthological Soc*. 2002, *21*(*2*), 238–252.	48
Trochine C. et al. Filamentous green algae inhibit phytoplankton with enhanced effects when lakes get warmer. *Freshw Biol*. 2011, *56*(*3*), 541–553.	37
Gladyshev MI, Gubelit YI. Green Tides: New Consequences of the Eutrophication of Natural Waters (Invited Review). *Contemp Probl Ecol*. 2019, *12*(*2*), 109–125.	31

According to the most cited papers and analysis of citations, the most relevant research topics which address *Spirogyra* spp. blooms, are (i) eutrophication of Lake Baikal [6]; (ii) triggers for macroalgal outbreak [34,35]; (iii) consequences of dreissenid invasion to the lakes; (iv) interactions between macroalgae and phytoplankton.

3.4. Ecological Assessment, Based on Opportunistic Macroalgae

The list "Ecological assessment with macroalgae" included 145 papers. Since the goal of the search was focused on the methods and indices based on opportunistic macroalgae, the number of papers is less than in the previously published recent review [9]. According to the Scopus database, the first paper on this topic was published in 1973 and enlightened the issue of the surface area or coverage in ecological assessment on the example of coral reefs [36]. Water Framework Directive (WFD) (Directive 2000/60/EC) [7] and The EU Marine Strategy Framework Directive (MSFD, Directive 2008/56/EC) [8] have served as an impetus for the development of this issue. The sharp increase in the number of papers started in 2000's and intensified in 2010's as was previously shown for studies focused on macroalgal blooms.

The leading countries in this topic are arranged in the following order: (i) Italy (20 papers); (ii) China and Spain (19 papers for every country), (iii) the United States (18 papers), (iv) Brazil (11 papers).

The most cited papers from the list are referred in Table 4

Table 4. Ten of the most cited papers on ecological assessment with an application of opportunistic macroalgae.

Paper	Number of Citations
Borja A, Dauer DM. Assessing the environmental quality status in estuarine and coastal systems: Comparing methodologies and indices. *Ecol Indic.* 2008, *8*(*4*), 331–337.	274
Ballesteros E et al. A new methodology based on littoral community cartography dominated by macroalgae for the implementation of the European Water Framework Directive. *Mar Pollut Bull* 2007, *55*(*1–6*), 172–180.	256
Simboura N. et al. A synthesis of the biological quality elements for the implementation of the European Water Framework Directive in the Mediterranean ecoregion: The case of Saronikos Gulf. *Ecol Indic*. 2005, *5*(*3*), 253–266.	139
Juanes JA et al. Macroalgae, a suitable indicator of the ecological status of coastal rocky communities in the NE Atlantic. *Ecol Indic*. 2008, *8*(*4*), 351–359.	137
Nielsen R et al. Distributional index of the benthic macroalgae of the Baltic Sea area. *Acta Bot Fenn.* 1995, 155.	130
Deegan LA et al. Development and validation of an estuarine biotic integrity index. *Estuaries*. 1997, *20*(*3*), 601–617.	128
Wells E et al. The use of macroalgal species richness and composition on intertidal rocky seashores in the assessment of ecological quality under the European Water Framework Directive. *Mar Pollut Bull.* 2007, *55*(*1–6*), 151–161.	112
Orfanidis S. et al. Ecological Evaluation Index continuous formula (EEI-c) application: A step forward for functional groups, the formula and reference condition values. *Mediterr Mar Sci*. 2011, *12*(*1*), 199–231.	101
Dahl AL. Surface area in ecological analysis: Quantification of benthic coral-reef algae. *Mar Biol.* 1973, *23*(*4*), 239–249.	87
Hu L et al. Remote estimation of biomass of *Ulva prolifera* macroalgae in the Yellow Sea. *Remote Sens Environ*. 2017, *192*, 217–227.	85

According to the most cited papers, the most relevant topics which address opportunistic macroalgae in the ecological assessment are: (i) development and improvement of methodology and indices [37–39], (ii) adaptation of existing methodology to the European Water Framework Directive [40,41], (iii) evaluation of the main metrics [42], (iv) remote sensing in the assessment of green tides [43].

4. Application of Opportunistic Macroalgae in Ecological Assessment

4.1. Freshwater Ecosystems

4.1.1. *Cladophora* spp. Blooms

Opportunistic macroalgae can be used to assess eutrophication in freshwater ecosystems. For example, in the American Great Lakes, the observations of macroalgal blooms have been continuing for a few decades. One of the first records of a mass occurrence of macroalgae *Cladophora glomerata*, as a sign of eutrophication, was made in the Great Lakes in the 1930s [44]. Since the middle of the XX century, there have been many studies on *C. glomerata* seasonal dynamics, the influence of environmental conditions, and phosphorus loading on photosynthesis, growth rate, algal coverage, and biomass [45–47]. Finally, *C. glomerata* biomass at the level of 50 $gDWm^{-2}$ was proposed as a threshold value for "bloom" or "nuisance" conditions [5,45]. A positive relationship between *C. glomerata* biomass and phosphorus concentration in water was taken as a basis for the measures on a decrease in nutrient loading [48]. With the decline of phosphorus loading, the biomass of *C. glomerata* also started to drop down, and during 1972–2006, it decreased by 25–60%. For example, in 1972, in Lake Ontario, *C. glomerata* biomass reached 400 gDW m^{-2}, then in 2006, it was less than 100 gDW m^{-2} [49]. However, in the 2000s, an invasion of dreissenid mussels to the Great Lakes caused an increase in water transparency and led to significant changes in the depth distribution of macroalgae. This, in turn, resulted in an increase in their biomass and coverage [50]. By the end of the 2000s, *C. glomerata* coverage was 57% in Lake Ontario [5], exceeded 80% in Lake Michigan [51], and reached 100% on the available substrate at the northern shore of Lake Erie [49].

After the dreissenid invasion, researchers distinguished pre-dreissenid and post-dreissenid periods. The first period reflects the nutrient conditions after the implementation of the measures on the decrease in phosphorus loading, and the second period reflects mussels-caused changes in nutrient cycling [50]. In addition to the filtering activity, mussels serve as local sources of bioavailable phosphorus, which directly influences biomass and growth of *C. glomerata* [52]. It was shown that a defined biomass threshold clearly reflects the proximity of local nutrient sources, and, together with data on nutrient stoichiometry in *C. glomerata* tissues, it can be applied for modeling [45]. The last model, proposed by Auer et al. [48], showed good prognostic results for eutrophication and macroalgae dynamics. This model included simulations of hydrodynamics, phosphorus-phytoplankton dynamics, and *C. glomerata* growth. It was shown that in the areas with local sources of bioavailable phosphorus (e.g., dreissenid colonies), the effectiveness of phosphorus uptake by macroalgae exceeded those of phytoplankton [48,52]. Modeling allowed the authors to propose a more effective way of wastewater management for better control of *C. glomerata* biomass and eutrophication in modern, post-dreissenid conditions [48]. Thereby long-term studies on *C. glomerata* communities in the American Great Lakes allowed defining threshold biomass as a metric for ecological assessment and application growth rate and tissue stoichiometry for effective modeling and management.

4.1.2. *Spirogyra* spp. Blooms

Macroalgae of the genera *Spirogyra* (Charophyta) also are able to form massive blooms in lakes. The most famous case of regular blooms has been known as Lake Baikal since 2012 [6]. High biomass of *Spirogyra* sp. (100–135 g of wet weight per m^2) was recorded in the proximity of areas with intense human activity, while these algae were almost absent at the sites, which are far from permanent human settlements [53]. Mass development of *Spirogyra* spp. in Lake Baikal has caused serious consequences: replacement of endemic populations of species of the genus *Draparnaldioides* (Chlorophyta) at 3–10-m depth and formation of decaying algal mats [54,55]. Study of *Spirogyra* spp. blooms are hampered by difficulties in species identification, which can be based only on the fertile morphology of specimens and molecular analysis [56]. So far in Lake Baikal, 15 taxa of the genera *Spirogyra* were recorded, including one intraspecific taxon [56]. Lake Baikal is unique among great freshwater lakes: it has a high number of endemic species and a particular benthic ecosystem [53–56]. Baikal benthic vegetation has a clearly impressed vertical zonation: (i) the upper belt is formed by *Ulothrix zonata* (Chlorophyta) Kutz. at the depth 0–1.5 m, (ii) the second belt is formed by two dominant species *Tetraspora cylindrica* (Wahl.) Ag. var. *bullosa* C. Meyer (Chlorophyta) and *Didymosphenia geminata* (Lingb.) M. Schmidt (Bacillariophyta) at a depth of 1.5–2.5 m and (iii) third vegetation belt at the depths from 2.5–3.5 m to 10–12 m is formed by dominant endemic species of the genus *Draparnaldioides* K.I.Meyer & Skabitschevsky (Chlorophyta) [53]. The third vegetation belt is the most vulnerable to *Spirogyra* spp. blooms because it has the most favorable hydrodynamic conditions for the development and accumulation of this filamentous species. e.g., at a depth of over 2 m, the percent cover of filamentous algae reached 40–100% with a length of filaments to 50–70 cm in some areas of the lake [53]. The ability of *Spirogyra* spp. to live in plankton allowed these algae also to spread in planktonic communities. In the most eutrophied areas of the lake, the biomass of *Spirogyra* spp. in phytoplankton could reach 78 g m^{-3} [54]. Due to the occurrence of *Spirogyra* spp. in both planktonic and benthic communities, researchers apply the following parameters for assessment: (i) biomass, (ii) abundance, and (iii) coverage. Since the benthic and planktonic communities of Lake Baikal are unique and have high diversity, for ecological assessment, even in conditions of opportunistic blooms, there are widely applied classical indices: Shannon's species diversity index, dominance index, and equitability [53].

4.1.3. Rivers and Streams

Rivers and streams also meet mass occurrences of filamentous algae [57], but an ecological assessment for lotic systems is mostly based on Diatom indices [58]. For example, for urban creeks in Melbourne, which faced mass development of opportunistic *Cladophora-Stigeoclonium* community, it was proposed to use a Biomass index, which was calculated from the length of filaments and density of algae (cover code) [57]. Values of cover code were defined as 1 = 1–5% of algal cover throughout the habitat, 2 = 6–25%, 3 = 26–50%, 4 = 51–75%, 5 = 76–95%, 6 = 96–100%. The length of filaments varied from 5 to 100 cm. The suggested method seems to be very useful for fast, immediate assessment of a place and can show deterioration of the lotic habitat. However, it doesn't take into account the thickness of algal mats and cannot reflect the real biomass of filamentous macroalgae.

Quite recently, the new method RAPPER was proposed for the assessment of the risk of eutrophication in rivers as a complement to a diatom-based assessment of ecological status [58]. This method implies the separation of algal species on "stress-tolerant" (S-taxa) and "competitive" taxa (C-taxa), depending on their preference for sites with low or high nutrient input. The RAPPER method was proposed by authors to local managers for fast identification of the habitats which are exposed to high nutrient supply. It includes sampling for species identification and also implies the possibility of identifying with the naked eye the genera of macroalgae with extensive growth. RAPPER should be estimated on the basis of algal cover (on a nine-point scale) and the ratio between S-taxa and C-taxa. A comparison of RAPPER results with the Diatom Trophic Index has shown a good correlation [58].

4.1.4. Macroalgae as a Tool for Sanitary Assessment of a Recreational Area

Studies on the microbial community of opportunistic freshwater filamentous algae and accumulated algal mats have shown that they can be useful tool in the sanitary assessment of recreational areas [59]. On the Great Lakes, it was shown that *C. glomerata* mats are able to accumulate enterobacteria, including *Salmonella*, *Clostridium*, *Enterobacter*, and

Kluyvera [59,60]. Further findings showed that the number of enterobacteria (*Escherichia coli*) was much higher in *Cladophora* mats than in surrounding water [61]. There hasn't been found any correlation between the number of bacteria in algal mats and routine samples from the beaches [61]; however, later on, the example of the algae from the freshwater part of the eastern Gulf of Finland, was found that pathogenic bacteria *Salmonella enteritidis* may survive and propagate in decomposing *C. glomerata* mats [62]. Detailed study of microbial communities in decaying *C. glomerata* mats has shown that simultaneously with a drop in microbial diversity, an abundance of enteric and pathogenic bacteria increased [60]. Based on these findings, it can be proposed that the enumeration of bacteria in algal mats, together with accounting of algal biomass, can be a useful tool for the fast assessment and prediction of sanitation and hygiene status of resort areas. Moreover, regular harvesting of algal biomass in areas with regular macroalgal blooms can significantly improve the sanitary status of the beaches because filamentous macroalgae can serve as a natural collector of pathogens. This method of assessment can be applied only in freshwater ecosystems because marine macroalgae are well-known for antibacterial activity [62,63].

4.2. Assessment of the "Green Tides" and Algal Mats in Brackish Water Ecosystems in a Case of the Baltic Sea

4.2.1. Coastal Habitats with Monodominant Communities

In the Baltic Sea, which characterizes by transitional conditions from freshwater to brackish water, the coastal eutrophication led to the formation of extensive algal mats formed by Chlorophyta (*Cladophora* and *Ulva*) and Ochrophyta (*Pylaiella littoralis*) algae [64,65]. These mats cover extensive areas at a depth of 3–5 m, where they can survive during winter and in spring to form new generations of macroalgae [65]. In freshwater parts of the Baltic Sea, communities of macroalgae are monodominant, with the prevalence of the species *Cladophora glomerata* and *Ulva intestinalis* [10]. For environmental assessment, the biomass and thickness of algal mats have been used widely [10,65]. Seasonal studies showed that the dynamics of opportunistic macroalgae in the Baltic Sea are typical: the growth starts in Spring when the water temperature reaches 10 °C and during summer forms one or two peaks of biomass, which are followed by the formation of algal mats with thickness till 30 cm and decaying biomass at the shore [62–65]. Initially, in the Baltic Sea, the area and thickness of mats had been used as a common indicator of eutrophication [64]. Later, the thickness of algal mats was proposed by Lauringson and Kotta [66] as a predictor of environmental conditions at the bottom. The authors concluded that algal mats with a thickness of less than 6 cm could have a positive effect and promote the settlement of aquatic invertebrates on previously decolonized bottom areas. However, algal mats with a thickness of more than 6 cm provoked hypoxia with negative consequences for the bottom fauna [66].

Berezina et al. [67], in the case of the coastal habitats in the eastern Gulf of Finland, developed an integrated approach, and, on the basis of algal cover (AC), the thickness of algal mats (TAL) and signs of hypoxia determined five classes of habitat quality: I—no macroalgae and/or no hypoxia signs under algal layer; II—living macroalgae present, but no any signs of hypoxia; III—living macroalgae, signs of hypoxia under the algal layer, spots of black sediment; IV—mix of living and dead macroalgae, black sediment under algal layer and smell of hydrogen sulfide; V—all or most of the algae are in different stages of decomposition, strong smell of hydrogen sulfide [67].

4.2.2. Coastal Habitats with Perennial Species

Towards the Danish Straits, with an increase in salinity, species composition in macroalgal communities is changing to the higher diversity and dominance of perennial species [68]. For the brackish water parts of the Baltic Sea, which is characterized by diverse algal communities, Rinne et al. [12] used cumulative algal cover and ratio of opportunistic and perennial species as an indicator of eutrophication. The authors reached the conclusion that this method should be applied carefully because it should be taken into account which species of algae consisted of cumulative algal cover and how other factors (water clarity and Secchi depth) may influence the ratio of opportunistic and perennial species [12].

Studies on the dynamics of coastal communities in different parts of the Baltic Sea have shown that the complex of dominating species highly depends on climatic conditions, in particular–on conditions of the winter period [69,70]. Alternating cold and warm winters lead to alternating dominant species. After a warm winter with an absence of ice cover, the perennial species *Fucus vesiculosus* colonizes the zone of opportunistic algae. In the case of cold winter, ice cover cleans off sprouts of perennial species from the substrate, which results in fast colonization by opportunistic species in springtime, followed by biomass outbreak [69]. However, a long period of warm winters, together with anthropogenic pressure, leads to intensified eutrophication accompanied by the mass development of opportunistic macroalgae [70]. Seasonal studies in the eastern Gulf of Finland confirmed significant climatic impact and have shown significant negative correlations between seasonal biomass of green filamentous macroalgae and wind speed, as well as an index of the North Atlantic Oscillation (NAO). At the same time the degree of the climatic effect depended on the landscape peculiarities of local habitats [71]. This natural impact creates difficulties for an adequate assessment of the coastal zone and requires choosing approaches and metrics carefully.

Similarly, to the Great Lakes, a recent study of the two opportunistic species *Cladophora glomerata* and *Ulva intestinalis* in the Baltic Sea has shown that concentrations of phosphorus in *Cladophora* strongly correlated with a distance from the source of eutrophication [72]. The authors proposed to apply phosphorus concentration in *Cladophora* as an indicator of long-term nutrient pollution.

Since in freshwater and brackish water habitats, macroalgal communities are dominated by one or two opportunistic species, methods of assessment are based on the use of such indices as biomass, coverage of substrate, the thickness of algal mats, stoichiometry, and signs of hypoxia.

4.3. Marine and Estuarine Ecosystems

4.3.1. Main Principles of Assessment in Marine and Estuarine Habitats

In coastal marine habitats algal communities are represented by a number of species, including perennial, which can be displaced by opportunistic macroalgae. Such distant methods as remote sensing and aerial photographs are widely used for the assessment of “green tides” and floating mats of macroalgae on a global scale. The main limitations of these methods are shallow penetration into the water column and difficulties in distinguishing species of macroalgae and seagrasses on pictures [9]. For the assessment in place, there are many indices and methods which were developed on many marine coastal habitats: for example, MarMAT (Marine Macroalgae Assessment Tool) [73], RSL (Reduced Species List) in the British Isles [74], etc. Many indices are based on the use of *Fucus* belts for assessment: frond density, frond length, frond-length/total frond-length ratio, and taxonomic richness of epibionts [75,76].

Since 2000 Water Framework Directive (2000/60/EC) (WFD) and Marine Strategy Framework Directive (MSFD) established the main principles for the use of macroalgae in environmental assessment. According to WFD, there should be considered composition, macroalgal cover, abundance, and disturbance-sensitive taxa [7]. MSFD, which requires all European marine waters to be in ‘Good Environmental Status’, extracted 11 descriptors, which include the main parameters of the ecosystem as a whole: biodiversity, alien species, fish stocks, food-webs, eutrophication, sea-bed integrity, hydro-morphology, contaminants in the sea, contaminants in seafood, litter, and introduction of energy/noise [8]. In addition to indices that are based on perennial communities, there were developed for evaluation with an application of opportunistic species.

4.3.2. Ecological Evaluation Index

One of the first indices which involved not only species composition and morphological groups but also took into consideration functional groups of macroalgae was the Ecological Evaluation Index (EEI) [77,78]. The EEI was adapted to WFD and divides marine benthic macrophytes into two groups: the late-successional with a thick or calcareous thallus, low growth rates, and long-life cycles (ESG I) and the opportunistic or annuals, sheet-like, and filamentous seaweed species with high growth rates and short life cycles (ESG II) [79]. ESG I and ESG II represent alternative ecological states, e.g., pristine and degraded [80]. During regular seasonal sampling, an absolute abundance of each group is estimated by coverage (%) in every sample. In addition to coverage, a calculation of this index also includes the surface area of sampling sites or the length of every transect. A numerical scoring system for the assessment of the ecological status of coastal and transitional waters represents five ecological categories: High, Good, Moderate, Low, and Bad, with corresponding values of EEI from 10 (High) to 2 (Bad) [69]. One of the virtues of this index is its easy application in areas with diverse species composition.

4.3.3. CFR and CCO Indices

Guinda et al. [81] compared the RSL (Reduced Species List) and CFR index, which includes calculating global cover of macroalgae, the occurrence of characteristic species, and the total cover of opportunistic species. It was shown that the CFR index responded more accurately to pollution gradients than the RSL index. The most sensitive indicators in the case of CFR were macroalgae cover population richness and proportion of opportunistic species [81]. Later CFR index was intercalibrated in accordance with WFD requirements (continuous scoring system, ranging from 0 (bad status) to 1 (high status) in accordance with the Ecological Quality Ratio (EQR)) and successfully applied in the southern Northeast Atlantic. CFR index has shown high sensitivity in both: subtidal and intertidal zones and can be recommended as a tool for the assessment of macroalgal communities [82].

Another index, which was developed at the base of CFR for temperate macroalgal communities with clearly impressed vertical zonation with belts of kelp, is called CCO for cover–characteristic species–opportunistic species [83]. Estimation of CCO includes three metrics: global plant cover, number of characteristic species, and cover by opportunistic species. The last metrics, in addition to the typical opportunistic macroalgae species from Ochrophyta, Chlorophyta, and Rhodophyta, there were included colonial microalgae, particularly Bacillariophyta [84]. Boundaries of the ecological status include five grades and vary from Bad status (0–19) to High (80–100). One of the virtues of this index is that there is no necessity to identify all species of macroalgae, which takes time, but enough to identify species which give no less than 1% of global plant cover in the studied area.

4.3.4. Opportunistic Macroalgal Blooming Tool

In accordance with WFD, there was developed an index Opportunistic Macroalgal Blooming Tool (OMBT) for the Atlantic coast of the UK [84]. OMBT is a complex index composed of five metrics and has values from zero (major disturbance) to one (reference/minimally disturbed) [84]. In OMBT next parameters are included: (i) percentage cover of the available intertidal habitat (AIH); (ii) total extent of area covered by algal mats (affected area (AA)) or affected area as a percentage of the AIH (AA/AIH, %); (iii) biomass of AIH (g m^2); (iv) biomass of AA (g m^2); (v) presence of entrained algae (percentage of quadrats). The four class boundaries are: (i) High/Good = 0.8; (ii) Good/Moderate = 0.6; (iii) Moderate/Poor = 0.4; (iv) Poor/Bad = 0.2 [84]. Since in estuaries, macroalgal blooms often are presented only by a few dominant species, authors excluded species composition from evaluation. When taking into account common peculiarities of opportunistic algal blooms, it is obligatory to make an assessment during the seasonal maximum of biomass. For more precision, the authors recommended taking samples regularly during the vegetative season because the peak of biomass may occur in the late spring as well as the mid-Summer [84].

5. Conclusions

Analysis of the Scopus database has shown that a sharp rise in published papers on the different aspects of the mass development of opportunistic macroalgae started in 2010's. The possible reason for this rise can be an increase in massive macroalgal blooms around the world, which started in the second half of the 2000's. Simultaneously with global changes in coastal ecosystems, there appeared a need for the improvement of existing evaluating systems. The development and implementation of WFD and MSFD served as an impetus for the development and adaptation of macroalgal indices. The long-term studies resulted in many diverse indices for the ecological assessment [9].

Characteristics of opportunistic communities, which are widely applied as the metrics in ecological assessment, are given in Table 5.

Table 5. The main metrics in ecological assessment are with the application of opportunistic macroalgae.

Type of Habitat	**Freshwater and Brackishwater Ecosystems with a Dominance of One or Few Macroalgae Species**	**Marine and Estuarine Ecosystems with High Species Diversity**
Metrics	1. Coverage of opportunistic species (%) 2. Biomass 3. Thickness of algal mats 4. Signs of Hypoxia 5. Cumulative algal cover 6. Ratio of opportunistic and perennial species 7. An area covered by algal mats	1. Species composition 2. Number of characteristic species 3. Total algal coverage (%) 4. Total cover of opportunistic species 5. Proportion of opportunistic species 6. An area covered by algal mats
Recommended time of sampling	Seasonal peak of biomass	

Mainly in marine habitats, the species diversity and abundance of macroalgae are regarded as the main important metrics [9]. In freshwater and brackish water ecosystems the coverage and biomass are the most useful metrics [7]. The main difficulties in the assessment of opportunistic species are related to the ephemeral nature of these communities, i.e., fast growth and short time of vegetation. Some authors have noted the necessity to investigate seasonal dynamics because adequate evaluation can be performed only during the peak of biomass [84]. Additionally, the high dependence of opportunistic communities on climatic factors [71] brings some difficulties. For instance, during monitoring, researchers can find opportunistic algae at different stages of development: from the start of growth to the stage of accumulated algal mats and decomposition. All these peculiarities demand an extended approach to the evaluation of ecological status and the necessity to have at least a few adequate tools which can be applied simultaneously. In our opinion, for opportunistic communities, in addition to biomass, these tools should include the evaluation of algal mats and signs of hypoxia. Visual determination of black sediments and the area, they cover, also is important because, even in the absence of algal mats, they are evidence of recent macroalgal blooms.

The ability of opportunistic species of macroalgae to the fast growth and accumulation of nutrients and pollutants opens perspectives for more widespread application of these species in bioindication [72]. There exist many research papers and reviews on this topic, but in the present paper, I would like to pay attention to two new potential directions, which were proposed above: indication of nutrient pollution [72] and use of macroalgae (*Cladophora* spp.) in freshwater habitats for assessment and improvement of sanitary status of coastal areas [52–59]. The first method, which was reported recently [72], gives new possibilities in monitoring on the long distances when the conservation of water samples for nutrient analysis can meet technical difficulties. The second method, which was proposed in this paper on the basis of early studies [61,62], opens additional ways to control and make a sanitary assessment of recreational areas on the coasts of freshwater reservoirs.

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