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SPECIAL FEATURE: REVIEW

Ecological and limnological bases for management of overgrown macrophytes

Modern lake ecosystem management by sustainable harvesting and effective utilization of aquatic macrophytes

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Abstract
There are many problems related to overgrowth of aquatic macrophytes in many lakes and rivers throughout the world; for instance, the harvesting costs in Lake Biwa have been increasing by 200 million Japanese yen a year (equivalent to 1.8 million USD). Historically, aquatic macrophytes were harvested for use as fertilizer in agriculture in Japan, but are no longer in use because chemical fertilizers promote plant growth more effectively and are easier and cheaper to use. Thus, developing effective ways to utilize aquatic macrophytes is important to resolve this issue. In addition, sustainably harvesting macrophytes is also important for aquatic ecosystem management because macrophytes play a key role in aquatic ecosystems as nursery grounds and refuges for other small organisms living in the littoral area. Therefore, management and effective utilization of macrophytes through sustainable harvesting may play an important role in the conservation of lake ecosystems. In this short review, a recycling system using anaerobic digestion (AD) of submerged macrophytes, which were sustainably harvested from lakes, and microalgal mass culturing with AD effluent were introduced as a new technique for the conservation of lake ecosystems.

Keywords Ecosystem managements · Aquatic macrophytes · Sustainable utilization · Anaerobic digestion · Mass culture of microalgae

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Introduction

Currently, overgrowth of aquatic macrophytes is causing various environmental problems worldwide (Abbasi et al. 1990; FAO 2002; Hussner 2012; Hussner et al. 2017; O'Sullivan et al. 2010; Santos et al. 2011). In Europe, especially invasion of alien species has resulted in problematic issues for the native vegetation and surrounding environments. Hussner et al. (2017) recently reviewed management methods for controlling the growth and expansion of invasive macrophytes. In Japan, floating and submerged macrophytes, including alien species, also grow excessively in several shallow lakes, ponds, and rivers (Asada 2012; Haga and Ishikawa 2011; Hamabata et al. 2012). For instance, over 90% of the surface area of the south basin of Lake Biwa has been covered with submerged macrophytes for the last 2 decades (Haga 2015; Kawasaki 2015). Such excessive growth of macrophytes induces several environmental and social problems, e.g., it hinders fishery activities and boat traffic, produces bad smells, and presents ugly landscapes for residential people and tourists. Although a special committee

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was formed to discuss resolving these issues (Shiga Prefecture, Ministry of Land, Infrastructure and Transport 2009; Shiga Prefecture 2014; Kawasaki 2015) and several reviews on macrophyte management strategies have been published (Asada 2012; Ministry of Land, Infrastructure and Transport 2010), effective solutions have not been proposed yet.

Aquatic macrophytes play an important role in stabilizing water quality and providing spawning and nursery grounds for various fishes colonizing the littoral area (Carpenter and Lodge 1986; Haga 2015; Hilt and Gross 2008). Therefore, an appropriate quantity of macrophytes contributes to maintaining a healthy aquatic ecosystem. When considering conservation of an aquatic ecosystem, it might be important to know how to manage the biomass of the macrophytes in a system. Surprisingly, few studies have aimed to determine the appropriate biomass of aquatic macrophytes for maintaining a healthy aquatic ecosystem, although several studies have focused on the relationship of the fish-zooplankton-phytoplankton interaction and macrophyte abundance. For instance, in large-scale enclosure experiments, even small improvements in macrophyte abundances enhanced the zooplankton biomass and consequently increased the water clarity under no fish conditions (Schriver et al. 1995).

It is also important to know which methods to select to control the macrophyte biomass because various methods have been proposed (e.g., Hussner et al. 2017). Some previous studies have evaluated the methods for controlling the macrophyte biomass in lake ecosystems (Hussner et al. 2016, 2017; Lishawa et al. 2017; Xu et al. 2014). Mechanical harvesting and cutting submerged macrophytes are widely used measures, but carry some risks of spreading the macrophyte distribution by producing a lot of plant fragments and disturbing the bottom sediments. Xu et al. (2014) proposed harvesting appropriate amounts and appropriate timing for sustainable harvesting of *Trapa bispinosa* and consequently conservation of lake environments. A recent model simulation study showed that excess mowing might lead to a regime shift to a turbid phytoplankton-dominated state in eutrophic conditions with high external nutrient loading, although continuous mowing was effective for eradicating the macrophytes in oligo- and mesotrophic conditions (Kuiper et al. 2017).

Various aquatic macrophytes have been utilized for a number of purposes such as feeds, fuel, building materials, fertilizers, soil improvements, and water purification in the past and present (Little 1979). In Japan, the common reed *Phragmites australis* has been used for blinds, roofs, and flutes. Submerged macrophytes were even harvested for use as fertilizer around Lake Biwa until only 60 years ago (Hiratsuka 2011; Hiratsuka et al. 2006); old paintings of a panoramic view along the shore of Lake Biwa show the harvesting of submerged macrophytes by fishermen in the Edo era, more than 100 years ago (Fig. 1). According to a report on trading statistics in Shiga Prefecture in 1930–1938, sales volumes of macrophytes were 20,000–30,000 tons/year, and annual consumption of macrophytes with bottom sediments as a self-supplied fertilizer was 40,000–50,000 tons/year (Hiratsuka et al. 2006). Such extensive utilization may have prevented overgrowth of macrophytes in the past. Macrophytes, which grew utilizing nutrients provided from anthropogenic activities in lakes and rivers, were sustainably harvested and used as fertilizer for rice paddies and other farmlands and finally recycled to human society as agricultural products. Hiratsuka et al. (2006) called this previous recycling-oriented system with sustainable utilization of aquatic macrophytes the “Sato-umi” recycling-oriented society.

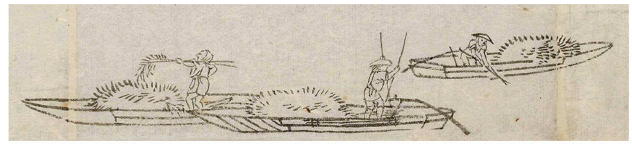

Fig. 1 View of the harvesting of submerged macrophytes, adapted from the ‘Sketch of the panoramic landscape of Lake Biwa’ by Haku-un Hirose in the late Edo era (courtesy of Otsu City Museum of History)

Currently macrophytes are no longer used as fertilizers because chemical fertilizers are better at promoting plant growth and are easier and cheaper to use. Therefore, one of the reasons for the recent problems with overgrowth of macrophytes might have been the use of chemical fertilizers instead of macrophytes, although excess nutrients accumulated in the lake bottom sediments during the eutrophication period, i.e., until the 1970s, could enhance macrophyte growth (e.g., Verhofstad et al. 2017). If an effective utilization of aquatic macrophytes is developed using modern technology, harvesting of macrophytes as a business will be revived, reducing the problem of their overgrowth.

In this short review, we introduce a concept for managing macrophyte abundance to maintain healthy and sustainable lake ecosystems and a fundamental technology to effectively use the macrophyte biomass harvested with brief results from our project, which was conducted at Lake Biwa, supported by the Ministry of the Environment, Japan, from 2014 to 2016. We explain it in four sections: (1) the appropriate biomass of macrophytes for sustainable harvesting and utilization, (2) effects of macrophyte harvesting methods on the water quality and bottom environments in the lakes, (3) effective treatment technology for macrophyte biomass with anaerobic digestion (AD), and (4) mass culturing of microalgal biomass using an AD effluent (ADE). The energy produced by AD using macrophytes to produce methane can be returned to human society as heat and/or electricity, and microalgae can be used as highly functional food supplements for aquaculture and livestock production. This novel recycling system using modern techniques, i.e., AD and microalgal culturing, could be helpful for the conservation of lake ecosystems through sustainable utilization of aquatic macrophytes.

Appropriate biomass of macrophytes for sustainable harvesting and utilization

In our project, the study site is the south basin of Lake Biwa (35˚20′N, 136˚10′E), which is located in Shiga Prefecture, a central part of the main island of the Japanese archipelago (Honshu) and the largest lake in Japan, having a surface area of 670 km^2, maximum depth of 103.6 m, and watershed area of 3174 km^2 (Kawanabe et al. 2012). The lake basin was divided into two parts, i.e., the shallow south (mean depth 3.5 m) and deep north basins (mean depth 44 m). It provides drinking water for 14.5 million residents in the Kansai region, including not only the Shiga Prefecture but also mega-cities such as Kyoto and Osaka.

There are intermittent records on the aquatic macrophyte stock in Lake Biwa from 1936 (Haga 2015). According to these records, the macrophyte stock in the lake during the growing season in 1936 was 3940 tons dry weight, but it declined to < 500 tons after 1950, probably because of turbidity caused by reclamation works and following eutrophication. After 1994, it increased again, reaching > 10,000 tons and finally 18,000 tons in 2014.

Shiga Prefecture started to harvest submerged macrophytes to eliminate invasive species, i.e., *Egeria densa* and *Elodea nuttallii*, after the late 1970s (Kawasaki 2015). Although the biomass harvested increased with increasing macrophyte stocks after 2000, reaching approximately 4000 tons/year in wet weight, it was just 4–5% of the stock in the south basin of Lake Biwa (Hamabata et al. 2012). More than 50–200 million yen/year (= 0.5–1.8 million USD/year) has been spent during the last 2 decades, suggesting that effective measures to solve this issue are urgently needed.

The submerged macrophytes play an important role as spawning and nursery grounds for fishes living in the littoral area and as refuges for fish flies and small animals associated with macrophytes (Jeppesen et al. 1998; Manatunge et al. 2000; Persson and Crowder 1998). As such, an appropriate biomass of macrophytes is needed to maintain healthy lake ecosystems. Surprisingly, pertinent information on macrophyte abundance is limited, as described above.

According to the periodic macrophyte biomass surveys carried out by Shiga Prefecture since 2002, the growing season for macrophyte assemblages in the south basin of Lake Biwa is the period from May to September every year, and the biomass in September has been estimated at an average of ca. 100,000 tons wet weight over the 10 years until 2011 (Haga and Ishikawa 2014). This indicates that monthly production is ca. 20,000 tons during the growing season. However, the growth curve of the macrophyte assemblages for each year fit well with a logistic model (authors' unpublished data). Although the growth curves showed year-to-year variation, the constants of the logistic equations, representing the growth rate, lag time for the growth, and maximum growth, strongly depended on three environmental parameters, i.e., water temperature, solar radiation and transparency, and macrophyte biomass in May, suggesting that the model can predict the maximum growth of the macrophytes using these four parameters during the early growing season.

Excessive growth of macrophytes prevents water movement and reduces the dissolved oxygen (DO) concentration just above the bottom of the lake, while too little growth reduces habitats for other organisms associated with macrophytes and consequently reduces their diversity (see also Ishikawa et al. 2018). Therefore, in our project, we tried to determine the appropriate biomass of macrophytes for maintaining a healthy lake environment using these two parameters, i.e., the DO just above the bottom and species diversity of animals attached to macrophytes. In the previous survey conducted at 52 sites in the south basin of Lake Biwa during 2014, DO just above the bottom decreased to levels below 4.0 mg l^{-1} at the sites where macrophyte abundances throughout the water columns as percentages of lake water volume infested with submerged macrophytes (PVI) were > 60% (see Ishikawa et al. 2018). The criterion for minimal or no impairment of production in non-salmonid fishes has been shown to be 5.0 mg l^{-1} of DO, and the acute lethal level of DO for fish in northern Alberta rivers is known to be 2.0 mg l^{-1} (Barton and Taylor 1996). The number of sites recorded at these critical levels of DO, 5.0 and 2.0 mg l^{-1} accounted for 13 and 8%, respectively, of the total number of sites located in the south basin of Lake Biwa (Ishikawa and Okamoto 2015). In addition, species diversity of animals attached to the macrophytes also declined below 30% PVI (Ishikawa et al. 2018). This PVI consisted of the threshold value of the ecologic regime shifting from clear to turbid waters (Canfield et al. 1984). This suggests that the lower limit of DO and the species diversity can be used as indicators for estimating the appropriate PVI of macrophytes to maintain a healthy aquatic ecosystem.

Effects of macrophyte harvesting methods on water quality and bottom environments

Currently, in Lake Biwa, submerged macrophytes are harvested with a harvester vessel (Super Kaitsuburi II) and a fork-shaped dredge, called a Man-gan (Fig. 2) (Kawasaki 2015). The former just cuts the upper part of the macrophyte bed, while the latter pulls up the whole body of the

Fig. 2 Fork-shaped shellfish collecting gear, the 'Man-gan,' modified to harvest submerged macrophytes in Lake Biwa (courtesy of Dr. Eiso Inoue)

macrophytes including the roots with bottom sediments by towing with a boat. It was shown that arsenic had accumulated in the upper part of the bottom sediment in the north basin of Lake Biwa (Takamatsu et al. 1985). Harvesting of macrophytes with a Man-gan disturbs the bottom sediment and might consequently re-suspend heavy metals and nutrients such as phosphate.

In our project, some experiments were conducted at two different sites, i.e., harvesting and non-harvesting sites, and the results were compared to evaluate the effect of harvesting on the water quality and bottom environment (Kohzu et al. 2018). Effects of disturbing the sediment surface with the collecting gear (short-term effect) and reducing macrophyte-related organic matter deposition by eliminating the macrophyte biomass (long-term effect) on the elution of heavy metals and nutrients from the bottom sediments were evaluated at both sites. For the short-term effect, alkaline earth metals (i.e., Ca, Mg, Sr), Fe ions, and inorganic nitrogen compounds were released from the sediment to the water column; consequently, the pH increased under oxygenated conditions at both macrophyte harvesting and non-harvesting sites. For the long-term effect, Mn, Fe, and As ions were released from the sediment under anoxic conditions at the non-harvesting site, while less of these three metal ions was released at the harvesting site. These results suggest that macrophyte harvesting might increase the risks to maintaining the water quality in the short term, but not in the long term. Therefore, the overgrowing macrophytes should be harvested by cutting just the upper parts, for example, by using a harvester vessel.

Effective treatment technology for macrophyte biomass with AD

Several treatments of macrophytes, e.g., bio-ethanol production and composting, have been proposed (Rabemanolontsoa and Saka 2012; Shiga Prefecture 2012), but no successful results had been reported until now. In our project, the submerged macrophytes were treated with AD and effectively transformed to energy by producing methane. AD technology has been well developed, and numerous studies exist (Appels et al. 2011; Carrere et al. 2016; Chandra et al. 2012). Several studies on AD using aquatic macrophytes (Koyama et al. 2014) have shown lower methane production than those using labile substrates such as food wastes (Verrier et al. 1987).

Some results on the AD of macrophytes obtained in our project are summarized in Fig. 3. The methane production from macrophytes varied among the species tested, depending on the lignin content (Koyama et al. 2014). Therefore, lower methane production was induced by lignin-rich macrophytes such as *Potamogeton maackianus*. Thus, delignification pretreatment should be applied to obtain sufficient methane production from the lignin-rich macrophytes. Alkaline thermochemical pretreatment prior to AD is one of the most effective pretreatments for the hydrolysis of lignocellulose (Fernandes et al. 2009; Xie et al. 2011). In our project, various pretreatments of NaOH loadings at 60 and 80 °C were applied to lignin-rich *P. maackianus* and lignin-poor *E. densa*, and hydrolysis tests were performed (Koyama et al. 2015). The hydrolysis efficiencies increased with increasing NaOH loading, and the highest efficiency was obtained at NaOH loading at a rate of 0.20 g per g total solid, 80 °C, and 3.0 h for both macrophytes. The methane yield of pretreated *P. maackianus* was 243 ml g^{-1} volatile solid, which is 51% higher than that of the untreated one, while that of pretreated *E. densa* was 24% higher than that of the untreated one (Koyama et al. 2015). These results suggested that alkaline thermochemical pretreatment could be an effective procedure for AD of lignin-rich macrophytes.

In Lake Biwa, the species composition of macrophytes varies seasonally, while the lignin content of *P. maackianus* does not vary much (Fujiwara et al. submitted). Methane production in AD using macrophyte assemblages collected from the lake depended greatly on the abundance of *P. maackianus*, which is the most dominant and lignin-rich species. This suggests that the species composition of macrophytes is important information for the stability of AD using field-collected macrophytes throughout the year.

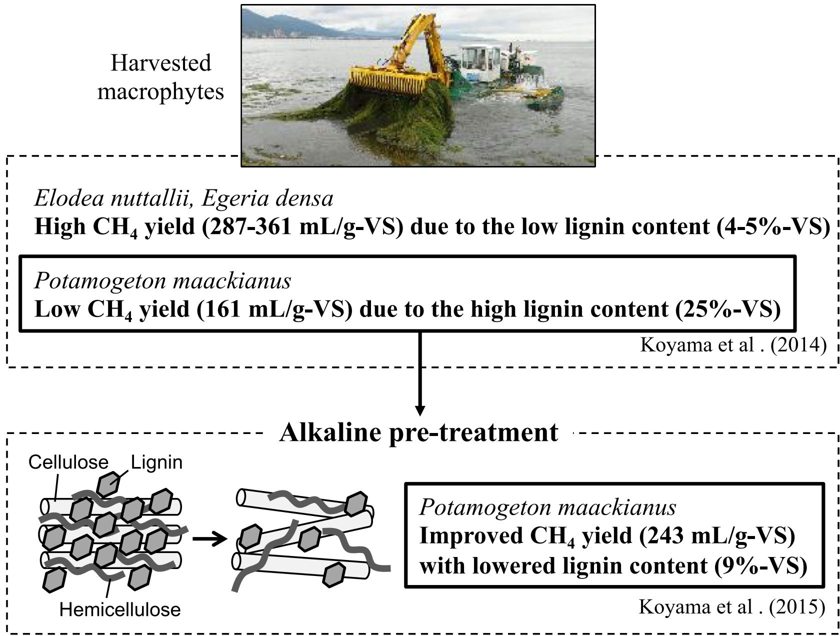

Fig. 3 Photo of harvesting macrophytes with a harvester vessel; lignin contents and methane yields from anaerobic digestion using lignin-poor *Elodea nuttallii* and *Egeria densa* and lignin-rich *Potamogeton maackianus* as substrates and those using alkaline pretreated *P. maackianus*. VS = volatile solid (after Koyama et al. 2014, 2015) (courtesy of Dr. Eiso Inoue)

In 200-l bench-scale experiments of our project, methane production and conversion efficiency in AD using alkaline thermochemical pretreatment macrophyte assemblages from Lake Biwa with and without food wastes were assessed daily over 4 months. Average methane conversion efficiency was 76% and 63%, while average methane production was 44 and 16 l kg^{-1} wet weight in the treatments with and without food wastes, respectively (Fujiwara et al. in preparation). During the study period, methane production was quite stable and higher for the treatment with than without food wastes, while its conversion efficiency reached > 60% in both treatments.

Mass culturing microalgal biomass using an AD effluent

Macrophyte biomass was effectively treated with AD and alkaline thermochemical pretreatment. However, it was difficult to dispose of the AD effluent (ADE) in the surrounding environments because it included considerable amounts of nutrients such as nitrogen and phosphorus (Ji et al. 2014). For instance, ammonium and phosphate concentrations in ADE using the macrophyte *E. densa* were 1200 and 80 mg l^{-1}, respectively (Kimura et al. submitted). In European countries, where livestock breeding is a major industry, ADE from livestock wastes is usually used in large pastures as manure. In Japan, however, it is difficult to directly use the ADE because of excess nitrogen loading, pathogenic microbes, and the unpleasant odor (Orzi et al. 2015).

Chemical contents of ADE resemble those of the growth media for microalgae such as *Chlorella*. In other words, nutrients in the ADE can be eliminated by growing the microalgae and transforming it to algal biomass. Microalgae are used as dietary supplements not only for humans but also for livestock (Wang et al. 2010). Valuable materials, such as biodiesel fuels (Chen et al. 2011) and astaxanthins (Dominguez-Bocanegra et al. 2004; Garcia-Malea Lopez et al. 2006), could be obtained from specific algal species.

Many studies have been carried out on mass culturing techniques in microalgae (De Pauw et al. 1984; Grima et al. 2009). Recently, the number of studies on culturing microalgae using ADE has increased (Xia and Murphy 2016), although microalgae that can tolerate large amounts of ammonium should be selected. Green algae and blue-green algae (or cyanobacteria) are known to show high ammonium tolerance (Collos and Harrison 2014), and *Chlorella* spp., *Chlamydomonas* spp., and *Arthrospira* spp. are frequently used for mass culturing (De Pauw et al. 1984; Grima et al. 2009). In our project, using several species of green algae, we investigated (1) the dilution rate of ADE for maximum algal growth, (2) whether ADE included essential or inhibitory materials for algal growth, and (3) the efficiency of eliminating nutrients such as nitrogen and phosphorus from ADE by culturing the algae.

In the table experiments, maximum algal growth was obtained in ten-fold diluted ADE. Nutrient enrichment of the diluted ADE led to enhanced algal growth, suggesting no inhibition but limited components for algal growth in ADE (Kimura et al. submitted). Enrichment just with magnesium with diluted ADE ensured maximum algal growth and reached > 80% removal rates of ammonium and phosphate from ADE. In the continuous culture using an outdoor 10-l reactor, 4.3–7.6 g dry weight of algal yields was obtained from 1 l of ADE, i.e., 1 kg wet weight of macrophytes,

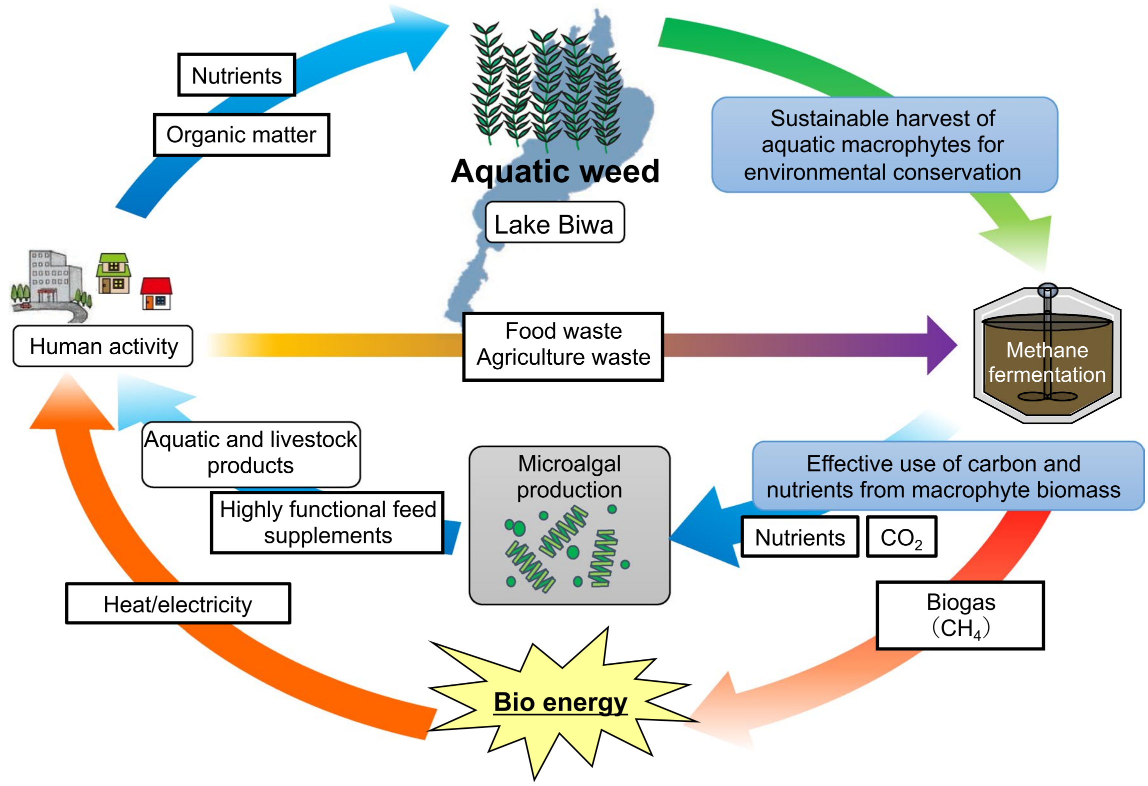

Fig. 4 Schematic diagram of the proposed concept of a 'recycling-oriented social system through sustainable utilization of macrophytes'

and both the ammonium and phosphate removal rates reached > 90% (data not shown).

Conservation of lake ecosystems and recyclong-oriented social systems through sustainable utilization of aquatic macrophytes

According to the periodic survey from 2002, aquatic macrophytes colonizing the south basin of Lake Biwa increased at a rate of 20,000 tons/month from May to September. This monthly increment of macrophyte biomass is usually called 'production' in ecology, meaning that this production can be recognized as one of the natural resources. A couple of indicators proposed in our project, i.e., DO just above the bottom and species diversity of animals attached to the macrophytes, can be helpful for estimating the appropriate quantity of macrophytes that must be harvested to maintain a healthy lake ecosystem.

A schematic diagram to explain our concept of a recycling-oriented social system is shown in Fig. 4. Aquatic macrophyte biomass can be transformed to energy through AD and biogas production. Simultaneously, nutrients in ADE can not only be eliminated but also transformed to valuable materials such as *Chlorella* by culturing algae. These two modern technologies are expected to play an important role in modern recycling-oriented social systems. Aquatic macrophytes may no longer be nuisances in the near future, but might be recognized as an important resource that must be used sustainably.

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