

Rewetting in Mediterranean reclaimed peaty soils and its potential for phyto-treatment use

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1 **Rewetting in Mediterranean reclaimed peaty soils and its potential for phyto-treatment use**

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8 **Highlights:**

1. Rewetting peaty soils, formerly drained for agricultural purposes, can contribute to increase the diversity of species in these ecosystems
2. The combined use of remote sensing and vegetation field surveys provides a snapshot at any given time of the surface colonized by the different plant communities and their development
3. *Phragmites australis* and *Myriophyllum aquaticum* can take up remarkable quantities of nitrogen and phosphorus from eutrophicated environment

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Abstract

A pilot experimental field combining rewetting of reclaimed peaty soils and water phyto-treatment was set up in the Massaciuccoli Lake basin (Tuscany, Italy) to reduce the water eutrophication and peat degradation caused by almost a century of drainage-based agricultural use.

In this paper, we investigated the restoration process occurring consequently to the conversion of a drained area in a natural wetland system (NWS) (the partial top soil removal, the realization of a perimeter levee to contain the waters, the rewetting with the drainage waters coming from the of surrounding cultivated areas) and the capability of the spontaneous vegetation to catch nutrients acting as a vegetation filter.

To follow the restoration process over time (2012-2016), we used a mixed approach merging phytosociological surveys with ortophotos taken by an Unmanned Aerial Vehicle (UAV). During the last year of observation (2016), we performed destructive sampling on the most widespread plant communities in the area (*Phragmites australis* and *Myriophyllum aquaticum* community) to quantify the biomass production and the uptake of nitrogen and phosphorus.

Stands of *Phragmites australis* (Cav.) Trin. ex Steud. yielded more than *Myriophyllum aquaticum* (Vell.) Verdc. (4.94 kg m^{-2} vs 1.08 kg m^{-2}). *M. aquaticum* showed higher nutrient contents (2.04% of N and 0.35% of P), however *P. australis* was able to take up more nutrients within the NWS because of its larger cover and productivity.

In the perspective of maximizing the plant development and consequently the amount of nutrients extracted from treated waters, the authors suggest 4-5 year-long-harvesting turns, better occurring in spring-summer.

Keywords:

Phragmites, *Myriophyllum*, phyto-treatment, UAV, wetland vegetation

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1. Introduction

Peatlands drainage and their following exploitation have severely compromised their ecological and biological status worldwide, because of the changes in the land use produced by agriculture, forestry and urbanization (Grootjans et al., 2012). We can estimate that nowadays less than 20% of the original, pristine wetland areas still remain (Verhoeven, 2014).

By altering groundwater patterns and compositions, extensive peatland drainage has determined significant changes on the physics and chemistry of peats, leading to: i) acceleration of organic-matter oxidation (Oleszczuk et al., 2008), with a consequent increase in greenhouse gases (GHG) emissions into the atmosphere of up to 25 t CO₂ equivalent ha⁻¹y⁻¹ (Wichtmann and Wichmann, 2011; Couwenberg et al., 2011); (ii) enhancement of mineralization and nitrification of organic N due to higher oxygen availability and consequent increase of NO₃⁻ concentrations in porewater (Tiemeyer et al., 2007) and (iii) mineralization of organic P compounds and increase of absorbed and Fe-bound P pools (Zak et al., 2004). The continual recurrence of these phenomena has negatively affected the status of peatlands, lowering the soil level (subsidence), increasing nutrient availability and loads delivered to receiving water bodies (eutrophication) and decreasing ecosystem biodiversity and functionality (loss of resilience) (Smolders et al., 2006; Pistocchi et al., 2012; Lamers et al., 2015).

Moreover, these deeply drained areas are becoming unsuitable for modern agricultural production requirements (Pfadenhauer and Grootjans, 1999) and almost inaccessible for the ordinary machines used in agriculture.

From a merely biodiversity perspective, peatlands are unique, complex ecosystems of global importance, since they contain many species found only or mainly in peatlands thanks to the water regime of these areas (Tanneberger and Wichtmann, 2011).

62 For all these above-mentioned factors considered, stopping the peatland drainage and planning the
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63 consecutive management represent an environmental priority to face.
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64 From literature, we can derive that there are different reasons leading to the change by moving from
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75 the traditional drainage-based management of peatlands: stimulating the restoration of land portion
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1066 deteriorated from prolonged drainage (e.g. restoring) or recovery of the agricultural productivity of
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1267 the areas (e.g. paludiculture).
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1568 Regardless the aims behind the restoration, we can assume that to achieve the rehabilitation of at
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1769 least some of the functions supplied by these ecosystems, two main conditions have to be met i)
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1970 rewetting (e.g. constructing dams or filling in drainage ditches) and ii) reduction of trophic status
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2271 (e.g. by mean of the top soil removal) (Van Dijk et al., 2007; Klimkowska et al., 2010 a,b; Zak et
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2472 al., 2014).
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2773 Both are not without side effects. Raising water level and flooding organic soils can lower the soil
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2974 nutrient availability (mainly released as ammonium), but can at the same time boost phosphorus
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3275 mobilization (Lamers et al., 2002; Meissner et al., 2008; Zak et al., 2004).
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3476 Top soil removal, i.e. the removal of the upper and most degraded peat layers responsible of the
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3677 higher mobilization of phosphorous during the rewetting phase (Zak and Gelbrecht, 2007; Zak et
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3978 al., 2017) causes the removal of the reproductive organs of plant species (seeds, stolons, rhizomes,
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4179 etc.) (Leps, 1999) delaying the time of re-naturation.
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4480 The case study reported in the present paper is linked to a project realized in Tuscany (IT), which
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4681 compares three different management strategies aimed to combine the peatland rewetting and the
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4982 water phyto-treating action.
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5183 In this paper, we focused on the Natural Wetland System (NWS). The first objective was to follow
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5484 the restoration process after rewetting of lowlands to evaluate the dynamics driven by the re-
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5685 established vegetation. According to literature, the ecological restoration perspective is highly
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5886 dependent on the zero-point condition before starting the restoration process (Klimkowska et al.,
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6187 2010b). Indeed, while Tanneberger and Wichtmann (2011) report that top soil removal in
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88 combination with rewetting can lead to the restoration of soft-water pools and small sedge marshes
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combination with rewetting can lead to the restoration of soft-water pools and small sedge marshes within 5 years, Poschlod (1992) shows that in the case of peatland severely used for peat extraction mostly monospecific stands of non-peat-forming species could develop even for 20 years after the rewetting. Joosten (1995) even reports that in the cases of severe anthropogenic impact on the environment, it is not possible to observe any change within a human time perspective.

The second important research goal was to evaluate the capability of the NWS to work as phyto-treatment system thanks to the capability of plants to take up nutrients from waters proportionally to the biomass production and nutrient contents in the vegetative tissues.

2. Material and Methods

2.1 Site description

The study was carried out over 5 years (2011-2016) in Vecchiano, about 10 km from Pisa, Italy (43° 49' 59.5''N; 10° 19' 50.7'') in the Migliarino, San Rossore, Massaciuccoli Natural Park, within a 15 ha experimental area (Fig.1a,b).

This site was used to compare the efficiency of three different strategies in treating the eutrophic drainage water coming from a cultivated sub-watershed within the reclamation district around the Massaciuccoli Lake. In this area, phosphorous has been recognized as the primary cause of the eutrophication and the losses of this nutrient from cultivated fields (dissolved + particulate fractions) are estimated in 2-4 kg ha⁻¹y⁻¹ (Pensabene et al., 1997; Bonari et al., 2013).

The NWS was set up as natural rewetted area with a surface area of 2.7 ha and surrounded by small embankments built with the top soil (~ 10 cm) removed long the area's borders. Natural elevation changes within the NWS helped in creating zones with a different bottom height in order to promote the colonization from a large variety of plant species.

The soils of this experimental area has been classified as Histosol according to the USDA system and as Rheic Histosol according to the FAO system (Pellegrino et al., 2015).

112 The climate is classified as Mediterranean (Csa) according to Köppen-Geiger climate classification
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113 map (Kottek et al., 2006). Summers are dry and hot, while rainfall is mainly concentrated in autumn
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114 and spring (mean annual rainfall = 910 mm) and mean air temperature at 2 m ranges from 6.6 °C to
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115 21.8 °C (mean= 14.6). Mean monthly temperatures and rainfall for 2011-2016 were recorded at a
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116 weather station closed to the experimental site, located in Metato (San Giuliano T., 5 m a.s.l.,
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117 611370 E UTM, 4847363 N UTM).
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118 The water level within the NWS was registered daily from December 2013 to August 2016. From
119 January 2013 to November 2013, the system was not equipped with a diver (CTD-Diver produced
120 by Schlumberger) for the water level measurement, thus manual measurements were performed
121 every 15 days (Tab.1).
122

123 The analyses of treated waters confirmed their eutrophic status with average annual total nitrogen
124 content ranging from 7.14 mg/L to 8.13 mg/L, the average annual total phosphorus content ranging
125 from 0.24 to 1.07 mg/L. About the soluble forms, the average annual Soluble Reactive Phosphorus
126 (SRP) ranged between 0.15 and 0.22 mg/L, while the average annual nitrates content varied from
127 1.41 to 3.23 mg/L.
128

129 **2.2 Trial setup and vegetation analyses**

130 The construction works lasted two years (2011 and 2012) and in January 2013 the phyto-treatment
131 system started to operate. The NWS's vegetation was periodically monitored from April 2013 up to
132 July 2016. Every year, in spring-summer, vegetation development and phytocenotic diversity were
133 surveyed using the Braun-Blanquet method (Braun-Blanquet, 1979). 30 Relevés were performed on
134 surfaces varying from 4 to 100 m² depending on the typology of the plant community. The used
135 nomenclature of the plants accords to Pignatti (1982) and Conti et al. (2005).
136

137 A multivariate analysis procedure using syntax software (Podani, 2001) was carried out for data in
138 vegetation surveys. The matrix of 48 species x 18 surveys was analysed according to UPGMA
139 cluster algorithm analysis, applying the coefficient of similarity of Bray-Curtis. During the
140 monitoring period, NWS aerial photos were taken every summer by using a drone (Iris +, 3D
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138 Robotics) flying at 25 m of height and equipped with a camera (gopro hero 3 +, 12 Megapixel). To
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139 remove distortion and correct the image back to a rectilinear lens projection and to make photo
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140 mosaic, software Adobe Photoshop CC and Agisoft PhotoScan Professional Edition were used,
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141 respectively.
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142 At the given altitude, the obtained resolution was 1.75630 cm/pixel. Each orthomosaic has been
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143 created by composing 340 pictures, with a resulting reprojection error varying between 0.81 pixels
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144 to 8.43 pixels, with an average error equal to 2.47435 pixels.
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145 Aero photos were imported in GIS environment using Map Info ® 10.1 for geo-referencing and
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146 mapping, with an undetectable georeferenced error.
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247 The images were interpreted by assigning, manually, each digitized area to a specific
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248 phytosociological community (Fig.2).
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249 In July 2016, we performed a destructive sampling campaign aimed at the determination of the
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250 biomass production and nutrient concentration of the plant species grown within the NWS. The
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164 1150 °C (DIN EN 15104, 2010; DIN EN 14961-1, 2010). Phosphorus concentration was
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165 determined through photometrical determination (Murphy and Riley, 1962) after acidic digestion in
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166 a microwave digestion (EPA method n. 3052).
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167 To validate the laboratory methods, a standard biomass of *P. australis* (Netherlands, BIMEP 412)
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168 was used (WEPAL, 2011).
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169 The estimate of biomass production of the tested area (2.7 ha) was based on an upscaling process of
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170 the data collected at plot level. For both most represented mono-specific plant populations (*P.*
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171 *australis* and *M. aquaticum*, separately), we verified whether the mean production of each sampled
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172 areas were statistically different. Data were processed using the F-test in one-way ANOVA (version
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173 9.1; SAS Institute Inc., Cary, NC, USA), with the homogeneous sub-areas as factors (groups) each
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174 of them replicated three times by using an elementary sampling area of about 1 m². Two of the main
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175 assumptions of ANOVA (normal distribution and homogeneity of variance) were verified in this
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176 regard. The Duncan honest significant difference test was used for post-hoc means comparison at
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177 the 0.05 *p*-level only when the differences among factors used to be significant.
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178 Then, each statistically different value of biomass production per unit area was multiplied by the
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179 respective cover surface, so to obtain the contribution of two species to the total plant biomass
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180 production of NWS. The other cover types were not considered because they were either non-
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181 productive (uncovered area), or too little extended (*Typha latifolia*), or several species mixed (wet
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182 meadow).
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183 The N, P and C concentration of *P. australis* and *M. aquaticum* were transformed in arcsine to fulfil
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184 the assumptions of ANOVA and processed as described above.
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185 Nutrient uptake (kg ha⁻¹) was calculated as the product of nutrient concentration (nitrogen,
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186 phosphorus) and dry biomass weight.
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55 187 **3. Results**

56 188 **3.1 Flora and vegetation**

189 The multivariate analysis on the data of the most representative phytosociological relevès (n.18)
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190 led to the identification of four plant communities: 1- *Phragmites australis* community, 2-
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191 *Myriophyllum aquaticum* community, 3- *Typha latifolia* community, 4- wet meadows (Tab. 2, Fig.
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193 Floristic traits and physiognomic aspects confirmed the equipollence between the surveyed
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194 vegetation and the phytocoenosis widely spread on the neighbouring Massaciuccoli Lake (Bertacchi
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195 et al., 2015) and on the lacustrine areas of Tuscany, as well as described by Tomei et al., (1997).
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196 The first three communities are referable to *Phragmition communis* Koch 1926. The serial stage
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197 still in progress of wet meadow (which has been surveyed only from June 2014), did not allow us to
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198 reach a reliable assignment.
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24 3.2 Photointerpretation and vegetation mapping 25

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200 The ortophotos taken from the drone and re-organized one next to the other to recompose the whole
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201 area, allowed us to draw the development dynamics of the four above-cited plant communities over
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202 time (Fig.4).
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203 The implementation of the reconstructed photographic mosaic in GIS and the processing of digital
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204 data provided useful information about the fluctuations of the spatial pattern for the identified plant
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205 communities (Fig. 5).
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206 In Figure 5, the trends from 2012 to 2016 are reported. The area covered by *T. latifolia* was the
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207 lowest and almost stable in time (average 0.03 ha), while the area covered by wet meadow was, on
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208 average, the largest even if with wide fluctuations among the years (2.30 ha in 2013, 0.60 ha in
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209 2014, 0.02 ha in 2015 and 0.16 ha in 2016). The *M. aquaticum* pointed out a significant increase of
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210 the covered surface between 2013 and 2015 (from 0.04 ha to 0.70 ha), whereas it has been more
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211 than halved in the last year (0.34 ha). The development of the *P. australis* showed the shortest
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212 variations over time, increasing from 0.60 to 0.96 ha in the 2013-2015 period and drawing a little
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213 contraction in 2016 (0.78 ha).
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214 Overall, the total area covered by vegetation decreased from 2.24 ha in 2013, to 1.82 ha in 2014, to
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215 1.68 ha in 2015 up to 1.30 ha in 2016.
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216 **3.3 Biomass production and nutrients uptakes**

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217 The execution of the Saphiro-Wilk and Bartlett tests confirmed that the biomass production data
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218 were normally distributed ($W = 0.967$ and $W = 963$ for *P. Australis* and *M. aquaticum*,
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219 respectively) and their variances were homogeneous ($p > \chi^2 = 0.465$ and $p > \chi^2 = 0.295$ for *P.*
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220 *Australis* and *M. aquaticum*, respectively). Then we proceeded rightly to ANOVA analysis (Table
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221 3, Table 4).
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222 *P. australis* growth was statistically homogeneous within the NWS' embankments and we did not
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223 find significant differences among the identified sub-areas. The overall mean production was equal
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224 to 4.94 ± 1.67 (standard deviation) kg m^{-2} d. m. (dry matter) and the values from the different sub-
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225 areas ranged from 3.15 kg m^{-2} d. m. (sub-area 4) to 6.44 kg m^{-2} d. m. (sub-area n.9).
28

226 *M. aquaticum* was less productive than *P. australis* with a mean production of 1.05 ± 0.35 (s.d.) kg
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227 m^{-2} d. m. (weighted on the surface of each sub-areas). The sub-area 7 (1.43 kg m^{-2} d.m.) was
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228 significantly more productive than the other two (sub-areas 6 and 10) that were statistically
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229 equivalent between them (0.80 and 0.91 kg m^{-2} d. m., respectively).
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230 To estimate the biomass production within the NWS, we calculated the product of the mean
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231 production by the value of the corresponding area. Thus, we used the overall sample mean and the
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232 total surface occupied by *P. australis*, whereas we used the means of the sub-area 7 and the sub-
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233 areas 6 and 10 multiplied by the respective surface values, in the in the case of *M. aquaticum*.
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234 Summing up the biomass production from each homogenous area as described above, we obtained a
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235 total biomass production of 38.54 tons d. m. for *P. australis* and of 3.56 tons d.m. for *M. aquaticum*
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236 deriving from an occupied surface equal to 0.78 ha and 0.34 ha, respectively.
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237 About macronutrient content in biomass, there was not a significant difference in the nitrogen and
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238 phosphorous concentrations among the different sub-areas for both species.
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239 In *P. australis*, the detected values ranged between 1.55% and 2.03% for nitrogen and between
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240 0.14% and 0.19% for phosphorous, whereas in *M. aquaticum* the nutrients concentrations were
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241 higher varying from 1.88 to 2.20% for nitrogen and from 0.30 to 0.44% for phosphorous.
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242 The largest differences between the two species were observed on the phosphorous concentration
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243 whose mean concentration was equal to $0.17\% \pm 0.04$ (s.d.) in *P. australis* and $0.35\% \pm 0.09$ (s.d.)
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1244 in *M. aquaticum*. The mean concentrations of the two species were quite close in the case of
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245 nitrogen, although *M. aquaticum* showed again the higher values with $2.04\% \pm 0.29$ (s.d.) against
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246 $1.79\% \pm 0.21$ (s.d.) of *P. australis*.
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247 The nutrients taken up per unit area were equal to 882 kg ha^{-1} of N and 84 kg ha^{-1} of P for *P.*
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248 *australis* and 220 kg ha^{-1} of N and 38 kg ha^{-1} of P for *M. aquaticum*. From these data, we can derive
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249 that the total nitrogen taken up from the spontaneous vegetation growing within the NWS was 761
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250 kg, of which 688 kg taken up from *P. australis* (90%) and the remaining 73 kg taken up from *M.*
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251 *aquaticum* (10%).
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252 About phosphorus, *P. australis* contributed to take up 65 kg (83% of the total) while *M. aquaticum*
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253 to 13 kg (17% of the total).
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4. Discussion

4.1 Vegetation response to rewetting

From six years of observation, we can derive that the water level rising was successful in fostering
the development of hydro-hygrophilous species (Tab.2). Moreover, the species found were equal to
with those of the lacustrine ecosystems nearby in the Lake.

A critical phenomenon was the significant development of *M. aquaticum*. This exotic species of
South American origin, is considered invasive in Italy and can pose a threat to other hydrophitic
indigenous communities (Lastrucci et al., 2005). In our case, the species was already present in the
Massaciuccoli Lake area and was subsequently penetrated the NWS system.

263 About the vegetation, it was evident the predominance of the hygrophylous phytocoenosis, which
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264 showed a quick renaturation process, as evidenced by the wide surface covered by the different
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265 plant communities.

266 The spatial distribution of the vegetation species within the area showed the prevalence of the *T.*
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267 *latifolia* on the borders or in the strips surrounding the central nucleus of NWS system colonized by
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268 the *P. australis* population because of its higher competitive ability as reported by many authors
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269 (Findlay et al., 2002; Meyerson et al., 2002), especially under eutrophic conditions

270 The presence of a permanent water layer (30-35 cm) upon the bottom could justify the large
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271 distribution of *P. australis* and *M. aquaticum* within the NWS system. These species can prevail for
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272 long time and limit the development of other plants, which are not helophytes or are not provided
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273 with aerenchyma.

274 This behavior seemed to be proved by the wet meadows development that was largely widespread
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275 at the beginning of the re-naturation process (1.60 ha in 2013 and 0.60 ha in 2014) up to disappear
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276 almost completely in 2015 (0.02 ha). The partial recovery made in 2016 (0.16 ha) was to be related
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277 only with the temporarily drying up of some portions of the NWS (mostly occurred nearby the
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278 borders) that determined the regression of *P. australis* and *M. aquaticum* communities.

279 After an initial increase, the stabilization of the communities of *P. australis* and *M. aquaticum*,
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280 occurred in 2016, can be considered the result of their different ecological requirements, specific
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281 competitiveness and environmental conditions. Indeed *P. australis* is a rhizomatous helophyte, that
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282 needs to keep the overwintering buds under water but, for a part of the year, prefers to be in almost
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283 dry condition. In our case, the permanent flooding may have favored the hydrophytes as *M.*
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284 *aquaticum*, which spread in almost all the free spaces.

285 Although the situation monitored in 2016 is far from stable and we can expect continuous
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286 variations in the area covered by *P. australis* and *M. aquaticum*, it is reasonable to suppose that
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287 these will remain the two most important mono-specific plant populations within the NWS. Only
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288 the occurrence of no-ordinary disturbances (e.g. harvest, drought, fire) will be able to modify
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289 significantly the current vegetation cover to favor the development of others plant association types
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290 such as wet meadows or *T. latifolia*.

291 **4.2 Photointerpretation and vegetation mapping**

292 The mixed investigation method proposed, based on the merging of field surveys and remote
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293 sensing data, was particularly useful for the identification of the vegetation dynamics following a
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11 renaturation process. It seemed to be promising since it permitted the integration of methods acting
1294 on different scale (Klančnik et al., 2015) by combining the accuracy of a field level survey
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1495 (repeatability and the detectability) with the capability of remote sensing to extend the monitoring
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1296 over huge areas (Stroh and Hughes, 2010). Moreover, the proposed method was rather simple to use
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1997 and it did not require the purchase of expensive devices or sophisticated skills in computer science
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2198 or drones management.
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300 **4.3 Biomass production and nutrients uptakes**

301 The high productivity of *Phragmites australis* (4.94 kg m⁻² d.m.) was the effect of a series of
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31302 favorable conditions such as abundant water, high incident radiation, favorable growth
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33303 temperatures, highly nutrient availability and the sampling time choice (coincident with the highest
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36304 biomass productivity) as it is also confirmed by several studies conducted in unlimited nutrients
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38305 availability.
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41306 For example, Hocking (1989) registered 9.89 kg m⁻² d. m. at the peak of productivity in a nutrient-
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43307 enriched swamp in inland Australia. Gopal and Sharma (1982) reported production ranging from
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454608 7.50 to 9.30 kg m⁻² d. m. in nutrient enriched wetlands in India, while more recently Eid et al.,
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48309 (2010) showed a production of about 5.40 kg m⁻² d. m. in Egypt (Burullus Lake), data which are
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5110 quite similar to our average production.
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53311 In conditions of limited nutrient availability, the production of *P. australis* are definitely lower as
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555612 reported in literature: Aseada et al. (2002) up to 1.03 kg m⁻² d. m. in Austria; Karunaratne et al.
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58313 (2003) 1.98 kg m⁻² d. m. in Japan and Aseada et al. (2006) 0.69 kg m⁻² d. m. in Japan.
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314 Also for *Myriophyllum aquaticum*, mentioned in literature as parrot feather, many studies confirmed
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315 a positive correlation between relative growth rate and nutrient availability (Hussner et al., 2008).
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316 However the average yield we registered (1.08 kg m⁻² d. m.) was lower than that reported by
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317 Shybayama (1988) (2.80 kg m⁻² d. m., assuming a fresh weight/dry weight ratio equal to 0.21) or by
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318 Monteiro and Moreira (1990) (about 4.60 kg m⁻² d. m.), whereas are comparable with that
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319 registered by Sytsma and Anderson (1993) for a Californian experiment (about 1 kg m⁻² d. m.).
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320 These considerations, matched with the results of ANOVA, suggested that *P. australis* found
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321 favorable condition for its grown everywhere within the NWSs area, whereas *M. aquaticum* was
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322 penalized in some sub-areas and it could not reach a full productivity level. At this regard, we can
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323 speculate that the lower production of sub-areas 6 and 10 were due to the higher shading produced
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324 by *P. australis*, which colonized the nearest sub-areas.
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325 In consideration of the phyto-treatment purpose attributed to the restoration process, the capability
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326 of the plants of taking up nutrients from waters and storing them in their tissues can play an
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327 important role in determining the efficacy of this option. This feature is extremely important for
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328 phosphorus, for which the plant accumulation and subsequent harvesting can represent an effective
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329 way to cut down the nutrient loads in the treated waters. Differently, the role played by plants in
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330 nitrogen removal is less reliable in consideration of the losses of N through a gaseous phase
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331 (Vymazal, 2007).
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332 In our study, the mean amount of nutrients removed were high for *P. australis* (882 kg N ha⁻¹ and
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333 84 kg P ha⁻¹) and although lower, as well remarkable also for *M. aquaticum* (~220 kg N ha⁻¹ and
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334 ~38 kg P ha⁻¹).
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335 These quantities can be considered not so significative if compared with the nutrient loads which
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336 are delivered each year to the NWS (~ 1700 kg N ha⁻¹ y⁻¹ and ~ 130 kg P ha⁻¹ y⁻¹, by considering
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337 365 days of working per year, data not published), but there are some considerations that can
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338 deepen the real contribution of the plants in the nutrient abatement through the NWS.
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339 The first point concerns the development cycle of *P. australis* under natural growing conditions.
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340 Since no harvests were foreseen, inevitably a portion of nutrients up taken by plants was in the litter
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341 and residues fallen during fall-winter period. Indeed, as reported in literature (Graneli, 1984), leaves
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342 losses in *P.australis* contribute to reduce the total plant biomass of 28% (from summer to winter).
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343 This value was also confirmed by results published by Giannini et al. (2016, 2017).
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1344 Although the fate of these nutrients is uncertain, it is presumable that they remain immobilized
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349 portions left on the NWS bottom.

350 In our case study, harvesting during summer 2016 would have meant the removal of the yearly
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351 biomass produced by the reedbed during the 4th growing season while the previous annual
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352 productions were lying under the water layer. A gross quantification of the biomass produced
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353 during the previous 3 years can be tried multiplying the area covered by *P. australis* by the mean
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354 productivity registered during summer 2016, from which we estimate about 120 tons of dry biomass
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355 produced and not harvestable.

356 If this biomass presented the same average nutrient concentration detected in the biomass sampled
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357 in 2016, we could estimate about 2 tons of nitrogen and 200 kg of phosphorus taken up by the plant
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358 and largely fated to likely stabilization processes.

359 About *M. aquaticum*, Wersal and Madsen (2011) reported the strict connection existing between
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360 biomass production and nutrient availability, in particular the biomass is greater with at a high N/P
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361 ratio, which was also our case (N/P = 10). The negative relationship between yield and P
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362 concentration according to Wersal and Madsen (2011) could be explained with an increased
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363 competition for light and nutrients with algae.

364 In our case study, *M. aquaticum* registered a very high nutrients concentration per unit of dry
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365 biomass, which made it competitive with *P. australis* in term of nutrient uptake although the
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366 biomass production was definitely lower.

367 We can estimate a previous productivity of about 11 tons of dry biomass produced and not
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368 harvested, containing about 230 kg of total nitrogen and 40 kg of total phosphorus.

369 Comparing the overall estimated production on four-year perspective with the nutrient loads, we
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370 could access that the phyto-treatment capability of the ‘plant system’ raised up to 15% for total
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371 nitrogen and 20% for total phosphorus.

372 From a management perspective of NWS, an important point is related to the option of vegetation
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373 harvesting and thus, the effect that harvest time/cycle could have on the life span of the stands, on
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374 their productivity and their capability to take up nutrients. From the comparison with *P. australis*
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375 cultivated within the paludiculture system (PCS) (Giannini et al., 2017), we can derive some
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376 considerations. Indeed, while in NWS *P. australis* was unmanaged, in PCS was harvested every
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377 summer. This choice determined yield levels very different between the two systems. The
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378 production of 2016 was equal to 2.63 kg m⁻² d.m. for the PCS (unpublished data) versus 4.94 kg m⁻²
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379 d.m. for the NWS. Many authors reported a depressive effect of the summer harvest on *P. australis*,
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380 since the beds have not yet translocated all resources to rhizomes to guarantee a vigorous re-sprout
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381 in the next vegetative season (Graneli, 1990; Thompson and Shay, 1985). Moreover, recurrent
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382 mowing in flooded areas may amplify the negative effects of an early cut on productivity due to
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383 impaired convective ventilation and hypoxia on the basal part of the reed stands (Rolletschek et al.,
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384 2000).

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385 Despite the large nutrient availability, we can derive that the adoption of the PCS’ harvest strategy
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386 could determine in NWS a reduction of the growth potential of the reedbed especially in the first
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387 years of growing when the crop stand does not have a well-established underground reserve organs
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388 yet. After this phase, the annual cutting could increase the *P. australis* growth not only because the
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389 removal of dead culms favors the light interception by the new culms but also because the leaves,
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390 which are the organs photosynthetically active, are already completely lost (Graneli, 1989).

391 Thus, to maximize the phyto-treatment potential of the NWS, the best solution to adopt has can be a
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392 well-balanced harvest strategy by mowing *P. australis* every two years during summertime, after an
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393 initial phase of 4-5 unharvested years. In this way, we can favor the plant settlement without
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394 reducing significantly the reedbed life span (Gusewell et al., 2000).

395 In addition, the phyto-treatment ability of *M. aquaticum* is significantly enhanced by frequent
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396 harvesting (at least annually) (Nuttall, 1985) and we can partially repeat the considerations already
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397 expressed for *P. australis*.

398 However, this type of management can alter the renaturation process and preclude the possibility
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399 for the NWS to reach the climax conditions. Moreover, it is not to neglect that the deposit of the
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400 dead plant residue onto the NWS bottom can contribute to the formation of new peat and so
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401 reversing the actual trend of subsidence (Gessner, 2000; Domish et al., 2006) that constitutes a
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402 severe constraint for the agricultural use of the reclaimed area (Silvestri et al., 2017).

403 **5. Conclusions and implication for wetland management**

404 The conversion of drained peatlands to natural wetland resulted, under our experimental conditions,
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405 an operation quite easy and short to implement. Just few years after the flooding and the partial top
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406 soil removal, the restoration process seemed to be well underway as proved by the development of
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407 some floristic association typical of the surrounding palustrine areas. This fact confirmed that the
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408 status of peatlands was not as degraded as to prevent the spontaneous vegetation recolonization of
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409 the rewetted areas.

410 Although our experimental area (NWS) was not so widespread to be considered representative of
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411 the whole Massaciuccoli Lake catchment, was reasonable suppose that the main plant communities
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412 and associations able to colonize rewetted peatlands are those identified within the experimental
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413 area and that our results can be considered reliable for upscaling use.

414 In our experimental conditions, characterized by a large availability of nutrients and water
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415 *Phragmites australis* showed a remarkable biomass productivity and nutrients taken up. Although
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416 *M. aquaticum* had lower performances, we have to consider, for both species, the contribution
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417 derived from the nutrient portion within the biomass yearly fallen on the bottom of the system
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418 To increase furthermore the nutrient abatement capability of NWS, we can act optimise the harvest
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419 strategy. Indeed, the annual harvesting can increase the amount of nutrients removed from the
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420 system thanks to removal of harvested annual production. At same time, frequent cutting can
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421 penalize the plant growth during the initial phases, limit the peat forming process, make trouble in
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422 the management of the harvest operations (necessity of draining area or use of machines able to
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423 work in flooded conditions) and cause disturbance to the biota.
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424 For this reason, the management of NWS has to find a compromise able to meet different needs
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425 (multifunctional management).
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44
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47
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536 **Figure captions**

537 **Fig.1** (a) Aerial view of the Massaciuccoli Lake catchment (Tuscany, IT) and (b) zooming on the
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438 experimental area.
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439 **Fig.2** Aerial picture of the Natural Wetland System (NWS) with the location of the homogenous
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440 units identified for sampling. Areas n. 1, 2, 3, 4, 5, 8 and 9 are of *P. australis* (with sampling areas
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441 marked in orange)while areas n. 6, 7 and 10 are of *M. aquaticum* (with sampling areas marked in
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442 red).

443 **Fig.3** Dendrogram resulting from the cluster analysis of the relevès performed during the
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11 observation period. The numbers reported are referred to the relevès listed in Tab.2.
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15 **Fig.4** The diachronic mosaic of the vegetation succession of the NWS from 2012 to 2016. On left
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17 hand, the reconstruction from the ortophotos; on right hand, the sketch reporting the surface covered
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19 by each community year by year. The analysis reported is referred only to summer flights.
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22 **Fig. 5** Fluctuation of the cover values reached by different communities from 2013 to 2016.
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27 **Table captions**

28
29 **Tab.1** Mean water table levels for the different seasons over the years of observation. The reported
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31 values (h in mm) were measured relative to the weir at the outlet of the system.* is used to report
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33 period with water flow interruption for operation activities.
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37 **Tab.2** Table of the most representative phytosociological relevés (PH Phragmites australis
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39 community (Phragmitetum australis (Gams 1927) Schmale 1939); TY Typha latifolia community;
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41 MY Myriophyllum aquaticum community; WM Wet Meadows
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43 (Surveys n. 2,6,8,25,26,31,32 were performed in June 2014; n. 10, 12,27,28,29,33,34 were
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45 performed in June 2015; n. 13, 14,30,35 were performed in June 2016) (note: for index values, refer
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47 to the literature).
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51 **Tab.3** Results of ANOVA on the *P. australis* parameters. Within each factor, means in the same
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53 column followed by different letters are significantly different at $p < 0.05$ (Duncan test).
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56 **Tab.4** Results of ANOVA on the *M. aquaticum* parameters. Within each factor, means in the same
57
58 column followed by different letters are significantly different at $p < 0.05$ (Duncan test).
59

60 **References**

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63
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65

- 464 Asaeda, T., Hietz, P., Tanaka, N., Karunaratne, S. (2002). Seasonal fluctuations in live and dead
465 biomass of *Phragmites australis* as described by a growth and decomposition model: implications of
466 duration of aerobic conditions for litter mineralization and sedimentation. *Aquatic Botany* 73(3):
467 223-239.
- 468 Asaeda, T., Rajapakse, L., Manatunge, J., Sahara, N. (2006). The effect of summer harvesting of
469 *Phragmites australis* on growth characteristics and rhizome resource storage. *Hydrobiologia* 553(1):
470 327-335.
- 471 Bertacchi A., Lombardi T, Giannini V., Silvestri N., Bonari E. (2015). A case of ecological
472 renaturation in a drained mediterranean peatland: the case study of the Massaciuccoli lake basin
473 (Tuscany, It). 110° Congresso della Società Botanica Italiana onlus. II International Plant Science
474 Conference (IPSC). “Not only food: sustainable development, agro-biodiversity conservation &
475 human well being” Pavia, 14 - 17 September 2015
- 476 Bonari, E., Ercoli, L., Silvestri N. (2013). Introduzione al progetto e sintesi interpretativa. In:
477 Agricoltura e tutela delle acque nel bacino del lago di Massaciuccoli. Pacini Editore, Pisa (IT), 27-
478 37.
- 479 Braun-Blanquet, J. (1979). *Fitosociologia. Bases para el estudio de las comunidades vegetales*, 1,
480 819.
- 481 Conti, F., Abbate, G., Alessandrini, A., Blasi, C. (2005). *An Annotated Checklist of the Italian
482 Vascular Flora.*—Ministero dell’Ambiente e della Tutela del Territorio, Direzione per la Protezione
483 della Natura. Palombi ed.
- 484 Couwenberg, J., Thiele, A., Tanneberger, F., Augustin, J., Barisch, S., Dubovik, D., ... Joosten, H.
485 (2011). Assessing greenhouse gas emissions from peatlands using vegetation as a proxy.
486 *Hydrobiologia*, 674(1), 67-89.
- 487 DIN EN 14961-1 (2010) *Solid biofuels – Fuel specifications and classes –Part1: General
488 requirements.* Beuth Verlag , Berlin.
- 489 DIN EN 15104 (2010) *Solid biofuels - Determination of total content of carbon, hydrogen and
490 nitrogen - Instrumental methods.* Beuth Verlag, Berlin.
- 491 Domisch, T., Finér, L., Laine, J., Laiho, R. (2006). Decomposition and nitrogen dynamics of litter
492 in peat soils from two climatic regions under different temperature regimes. *European Journal of
493 Soil Biology* 42(2): 74-81
- 494 Eid, E. M., Shaltout, K. H., Al-Sodany, Y. M., Soetaert, K., Jensen, K. (2010). Modeling growth,
495 carbon allocation and nutrient budgets of *Phragmites australis* in Lake Burullus,
496 Egypt. *Wetlands*, 30(2): 240-251.
- 497 Findlay, S. E., Dye, S., & Kuehn, K. A. (2002). Microbial growth and nitrogen retention in litter of
498 *Phragmites australis* compared to *Typha angustifolia*. *Wetlands* 22(3): 616-625
- 499 Gessner, M. O. (2000). Breakdown and nutrient dynamics of submerged *Phragmites* shoots in the
500 littoral zone of a temperate hardwater lake. *Aquatic Botany* 66(1): 9-20.

- 501 Giannini, V., Oehmke, C., Silvestri, N., Wichtmann, W., Dragoni, F., Bonari, E. (2016).
502 Combustibility of biomass from perennial crops cultivated on a rewetted Mediterranean
503 peatland. *Ecological Engineering* 97: 157-169
3
- 4
504 Giannini, V., Silvestri, N., Dragoni, F., Pistocchi, C., Sabbatini, T., Bonari, E. (2017). Growth and
505 nutrient uptake of perennial crops in a paludicultural approach in a drained Mediterranean
506 peatland. *Ecological Engineering* 107: 478-487
8
- 9
507 Gopal, B., Sharma, K.P. (1982). Studies of wetlands in India with emphasis on structure , primary
508 production and management. *Aquatic botany* 12: 81-91.
12
- 13
509 Granéli, W. (1984). Reed *Phragmites australis* (Cav.) Trin. ex Steudel as an energy source in
510 Sweden. *Biomass* 4(3): 183-208.
14
15
- 16
511 Granèli, W. (1989) Influence of standing litter on shoot production in reed, *Phragmites australis*
512 (Cav.) Trin. ex Steudel. *Aquatic Botany* 35: 99-109.
18
19
- 20
513 Granéli, W. (1990). Standing crop and mineral content of reed, *Phragmites australis* (Cav.) Trin. Ex
514 Steudel, in Sweden—Management of reed stands to maximize harvestable biomass. *Folia*
515 *Geobotanica et Phytotaxonomica* 25(3): 291-302.
24
- 25
516 Grootjans, A. P., Van Diggelen, R., Joosten, H., Smolders, A. J., van An del, J., Aronson, J. (2012).
517 Restoration of Mires. *Restoration Ecology: The New Frontier*, Second edition, 203-213.
28
- 29
518 Güsewell, S., Le Nedic, C., Buttler, A. (2000). Dynamics of common reed (*Phragmites australis*
519 Trin.) in Swiss fens with different management. *Wetlands Ecology and Management* 8: 375-389.
30
31
- 32
520 Hocking, P.J. (1989). Seasonal dynamics of production, and nutrient accumulation and cycling by
521 *Phragmites australis* (Cav.) Trin. Ex Steuedel in a nutrient-enriched swamp in inland Australia. I
522 Whole plants. *Australian Journal of Marine Freshwater Research* 40: 421-444
36
- 37
523 Hussner, A., Meyer, C., Busch, J. (2008). The influence of water level and nutrient availability on
524 growth and root system development of *Myriophyllum aquaticum*. *Weed Research* 49: 73-80.
40
- 41
525 Joosten, J.H.J. (1995). Time to regenerate: long-term perspectives of raised bog regeneration with
526 special emphasis on paleoecological studies. In: Wheeler, B.D., Shaw, S.C., Fojt, W.J., Robertson,
527 R.A. (eds): *Restoration of temperate wetlands*. John Wiley & Sons, Chichester, New York,
528 Brisbane, Toronto, Singapore: pp. 471-494.
46
- 47
529 Karunaratne, S., Asaeda, T., Yutani, K. (2003). Growth performance of *Phragmites australis* in
530 Japan: influence of geographic gradient. *Environmental and Experimental Botany* 50(1): 51-66.
49
50
- 51
531 Klančnik, K., Zelnik, I., Gnezda, P., Gaberščik, A. (2015). Do Reflectance Spectra of Different
532 Plant Stands in Wetland Indicate Species Properties?. In *The Role of Natural and Constructed*
533 *Wetlands in Nutrient Cycling and Retention on the Landscape* (pp. 73-86). Springer International
534 Publishing.
56
- 57
535 Klimkowska, A., Kotowski, W., van Diggelen, R., Grootjans, A.P., Dzierza, P., Brzezinska, K.
536 (2010a): Vegetation Re-development After Fen Meadow Restoration by Topsoil Removal and Hay
537 Transfer. *Restor. Ecol.* 18: 924-933
58
59
60
61
62
63
64
65

- 538 W. (2010 b): Prospects for fen meadow restoration on severely degraded fens. *Perspect. Plant Ecol.*
539 *Evol. Syst.* 12: 245-255
2
3
540
4
5
541 Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F. (2006). World map of the Köppen-Geiger
542 climate classification updated. *Meteorologische Zeitschrift*, 15(3), 259-263.
8
9
543 Lamers, L.P.M., Smolders, A.J.P., Roelofs, J.G.M. (2002). The restoration of fens in the
544 Netherlands. *Hydrobiologia* 478: 107-130.
12
13
545 Lamers, L.P.M., Vile, M.A., Grootjans, A.P., Acreman, M.C., van Diggelen, R., Evans, M.G.,
14
546 Richardson, C.J., Rochefort, L., Kooijman, A.M., Roelofs, J.G.M., Smolders, A.J.P. (2015).
15
547 Ecological restoration of rich fens in Europe and North-America: from trial and error to an
16
548 evidence-based approach 90(1): 182-203.
18
19
549 Lastrucci, L., Foggi, B., Becattini, R. (2005). *Myriophyllum aquaticum* (Vell.)
20
550 Verdc.(Haloragaceae): una nuova specie esotica invasiva per la Toscana. *Informatore Botanico*
21
551 *Italiano* 37(2):1133-1136.
23
24
552 Lepš, J. (1999). Nutrient status, disturbance and competition: an experimental test of relationships
25
553 in a wet meadow. *Journal of Vegetation Science* 10(2): 219-230.
26
27
554 Meissner, R., Leinweber, P., Rupp, H., Shenker, M., Litaor, M.I., Robinson, S., Schlichting, A.,
28
555 Koehn, J. (2008). Mitigation of diffuse phosphorus pollution during rewetting of fen peat soils: a
29
556 trans-European case study. *Water, air & soil pollution* 188: 111-126.
31
32
557 Meyerson, L. A., Vogt, K. A., Chambers, R. M. (2002). Linking the success of *Phragmites* to the
33
558 alteration of ecosystem nutrient cycles. In *Concepts and controversies in tidal marsh ecology* (pp.
34
559 827-844). Springer Netherlands.
36
37
560 Monteiro, A., Moriera, I. (1990). Chemical control of parrotfeather (*Myriophyllum aquaticum*).
38
561 In *Proceedings of the 8th international symposium on aquatic weeds*, Uppsala, Sweden, 13-17
39
562 August 1990. (pp. 163-164). European Weed Research Society
41
42
563 Murphy, J., Riley, J.P. (1962): A modified single solution method for the determination of
43
564 phosphate in natural waters., *Analytica Chimica Acta* 27: 31-36.
45
46
565 Nuttall, P. M. (1985). Uptake of phosphorus and nitrogen by *Myriophyllum aquaticum* (Velloza)
47
566 Verd. Growing in a wastewater treatment system. *Marine and Freshwater Research* 36(4): 493-507.
48
49
567 Oleszczuk, R., Regina, K., Szajdak, L., Hoper, H., Maryganova, V. (2008). Impacts of agricultural
50
568 utilization of peat soils on the greenhouse gas balance. In: Strack, M. (eds) *Peatlands and Climate*
51
569 *Change International Peat Society*, Jyväskylä, Finland: 70-98.
53
54
550 Pellegrino, E., Bosco, S., Ciccolini, V., Pistocchi, C., Sabbatini, T., Silvestri, N., Bonari, E. (2015).
551 Agricultural abandonment in Mediterranean reclaimed peaty soils: long-term effects on soil
552 chemical properties, arbuscular mycorrhizas and CO₂ flux. *Agriculture, Ecosystems &*
553 *Environment*, 199: 164-175.
58
59
60
61
62
63
64
65

- 574 Pensabene, G., Frascari, F., Cini, C. (1997). Valutazione quantitativa del carico di nutrienti e di
575 solidi sospesi immesso nel lago di Massaciuccoli dai comprensori di bonifica di Vecchiano e
576 Massaciuccoli. In: Cenni M. (Ed.) Lago di Massaciuccoli. 13 ricerche finalizzate. Editrice
577 Universitaria Litografia Felici, Pisa (IT), 131-147.
- 578 Pfadenhauer, J., Grootjans, A.P. (1999). Wetland restoration in Central Europe: aims and methods.
579 Applied Vegetation Science 2: 95-106.
- 580 Pignatti, S. (1982). Flora d'Italia. 3 vols. Bologna: Edagricole.
- 581 Pistocchi, C., Silvestri, N., Rossetto, R., Sabbatini, T., Guidi, M., Baneschi, I., Bonari E., D.,
582 Trevisan, D. (2012). A simple model to assess nitrogen and phosphorus contamination in ungauged
583 surface drainage networks: application to the Massaciuccoli Lake Catchment, Italy. Journal of
584 environmental quality, 41(2): 544-553.
- 585 Poschlod, P. (1992). Development of vegetation in peat-mined areas in some bogs in the foothills
586 of the Alps. In: Bragg, O.M., Hume, P.D., Ingram, H.A.P., Robertson, R.A. (eds): Peatland
587 ecosystems and Man: An impact assessment. Department of Biological Sciences, University of
588 Dundee and International Peat Society. pp: 287-290.
- 589 Podani J. (2001). Syn-tax 2000. Computer program for data analysis in ecology and systematics.
590 Budapest. Scientia Publishing
- 591 Rolletschek, H., Rolletschek, A., Hartzendorf, T., Kohl, J.G. (2000). Physiological consequences of
592 mowing and burning of *Phragmites australis* stands for rhizome ventilation and amino acid
593 metabolism. Wetlands Ecology and Management, 8: 425-433
- 594 Shibayama, H. (1988). Ecology of aquatic weeds in creeks of the paddy growing area in the lower
595 reaches of the Chikugo river. Bulletin of the Kyushu National Agricultural Experiment Station
596 25(1): 1-75.
- 597 Silvestri, N., Giannini, V., Dragoni, F., Bonari, E. (2017). A Multi-adaptive framework for the crop
598 choice in paludicultural cropping systems. Italian Journal of Agronomy 12: 69-76.
- 599 Smolders, A. J. P., Lamers, L. P. M., Lucassen, E. C. H. E. T., Van der Velde, G., Roelofs, J. G. M.
600 (2006). Internal eutrophication: how it works and what to do about it—a review. Chemistry and
601 Ecology, 22(2): 93-111.
- 602 Stroh, P., Hughes, F. (2010). Practical approaches to wetland monitoring: guidelines for landscape-
603 scale long-term projects. Anglia Ruskin University, Cambridge.
- 604 Sytsma, M. D., Anderson, L. W. J. (1993). Biomass, nitrogen, and phosphorus allocation in
605 parrotfeather (*Myriophyllum aquaticum*). Journal of aquatic plant management 31: 244-248.
- 606 Tanneberger, F., Wichtmann, W. (2011). Carbon credits from peatland rewetting Climate-
607 biodiversity-land use: pp 223. Schweizerbart Science Publishers-Stuttgart.
- 608 Tiemeyer, B., Frings, J., Kahle, P., Kohne, S., Lennartz, B. (2007) A comprehensive study of
609 nutrient losses, soil properties and groundwater concentrations in a degraded peatland used as an
610 intensive meadow -Implications for re-wetting. J Hydrol 345:80–101

- 611 Thompson, D.J., Shay, J.M. (1985). The effects of fire on *Phragmites australis* in the Delta Marsh,
612 Manitoba. Canadian Journal of Botany 63:1964-1869.
2
- 613 Tomei, P.E., Guazzi E., Barsanti A. (1997). La carta della vegetazione delle paludi e del Lago di
614 Massaciuccoli. In: Lago di Massaciuccoli. 13 Ricerche finalizzate al risanamento. 2° contributo. Lo
615 stato delle conoscenze all'avvio delle opere di recupero ambientale. A cura di Mario Cenni. Ente
616 Parco Migliarino San Rossore e Massaciuccoli. Felici Editore, Pisa: 275-288.
8
- 617 Van Dijk, J., Stroetenga, M., van Bodegom, P.M., Aerts, R. (2007). The contribution of rewetting to
618 vegetation restoration of degraded peat meadows. Applied Vegetation Science 10: 315-324.
12
- 619 Verhoeven, J.T.A. (2014). Wetlands in Europe: Perspective for restoration of a lost paradise.
620 Ecological Engineering 66: 6-9.
15
- 621 Vymazal, J. (2007). Removal of nutrients in various types of constructed wetlands. Science of the
622 total environment 380(1): 48-65.
19
- 623 Wersal, R. M., Madsen, J. D. (2011). Influences of water column nutrient loading on growth
624 characteristics of the invasive aquatic macrophyte *Myriophyllum aquaticum* (Vell.)
625 Verdc. Hydrobiologia 665(1): 93-105.
24
- 626 WEPAL (2011) Certificate of analysis BIMEP (International Biomass Exchange Program).
627 Reference Material BIMEP sample 412 (*Phragmites australis*). Wageningen University of
628 Environmental Sciences. accessed at
629 [http://www.wepal.nl/website/download_files/consensus/BIMEP/BIMEP412 .pdf](http://www.wepal.nl/website/download_files/consensus/BIMEP/BIMEP412.pdf) on January 6,
630 2016
31
- 631 Wichtmann, W., Wichmann, S. (2011). Environmental, social and economic aspects of a sustainable
632 biomass production. J Sustain Energy Environ Spec Issue: 77-81.
35
- 633 Zak, D., Gelbrecht, J. (2007). The mobilisation of phosphorus, organic carbon and ammonium in
634 the initial stage of fen rewetting (a case study from NE Germany). Biogeochemistry, 85(2): 141-
635 151.
40
- 636 Zak, D., Gelbrecht, J., Steinberg, C.E.W. (2004): Phosphorus retention at the redox interface of
637 peatlands adjacent to surface waters in northeast Germany. Biogeochemistry 70: 357-368
44
- 638 Zak, D., Gelbrecht, J., Zerbe, S., Shatwell, T., Barth, M., Cabezas, A., Steffenhagen, P. (2014).
639 How helophytes influence the phosphorus cycle in degraded inundated peat soils – Implications for
640 fen restoration. Ecological Engineering 66: 82-90.
48
- 641 Zak, D., Meyer, N., Cabezas, A., Gelbrecht, J., Mauersberger, R., Tiemeyer, B., Wagner, C.,
642 McInnes, R. (2017). Topsoil removal to minimize internal eutrophication in rewetted peatlands and
643 to protect downstream systems against phosphorus pollution: A case study from NE Germany.
644 Ecological Engineering 107: 488-496.
54

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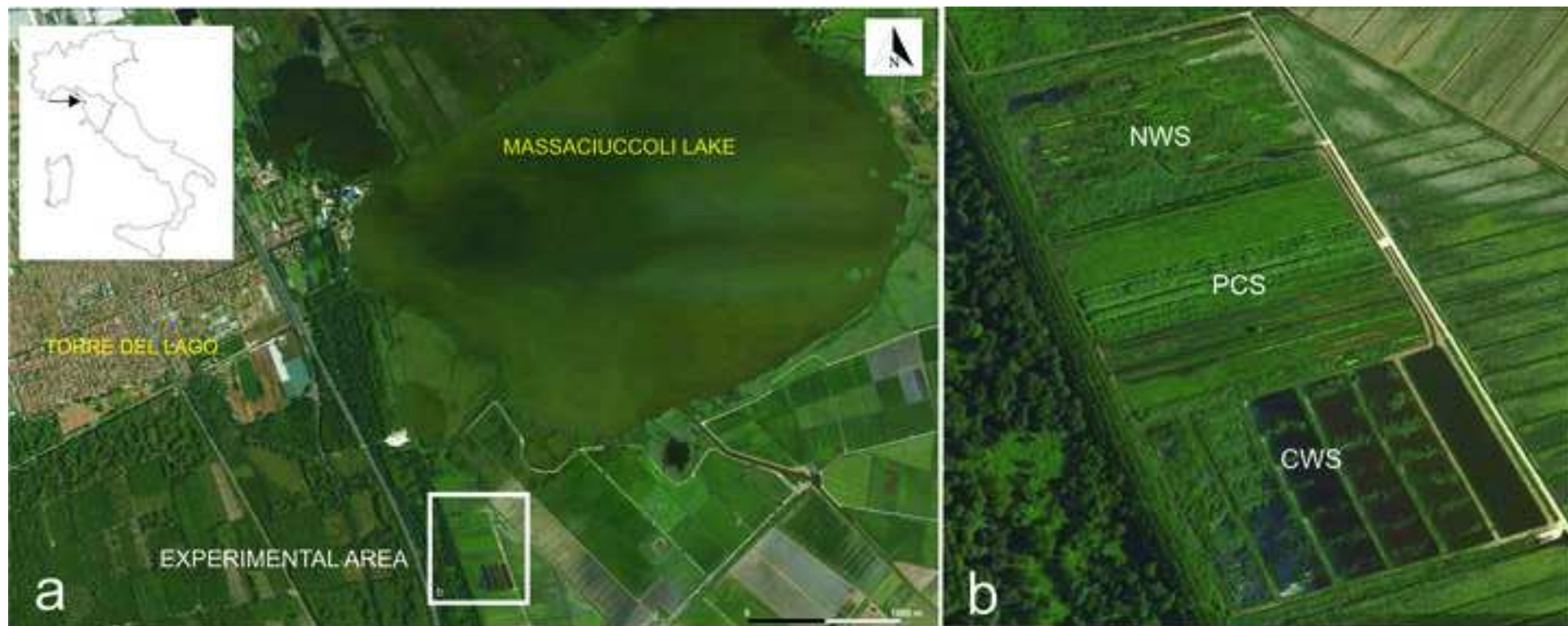


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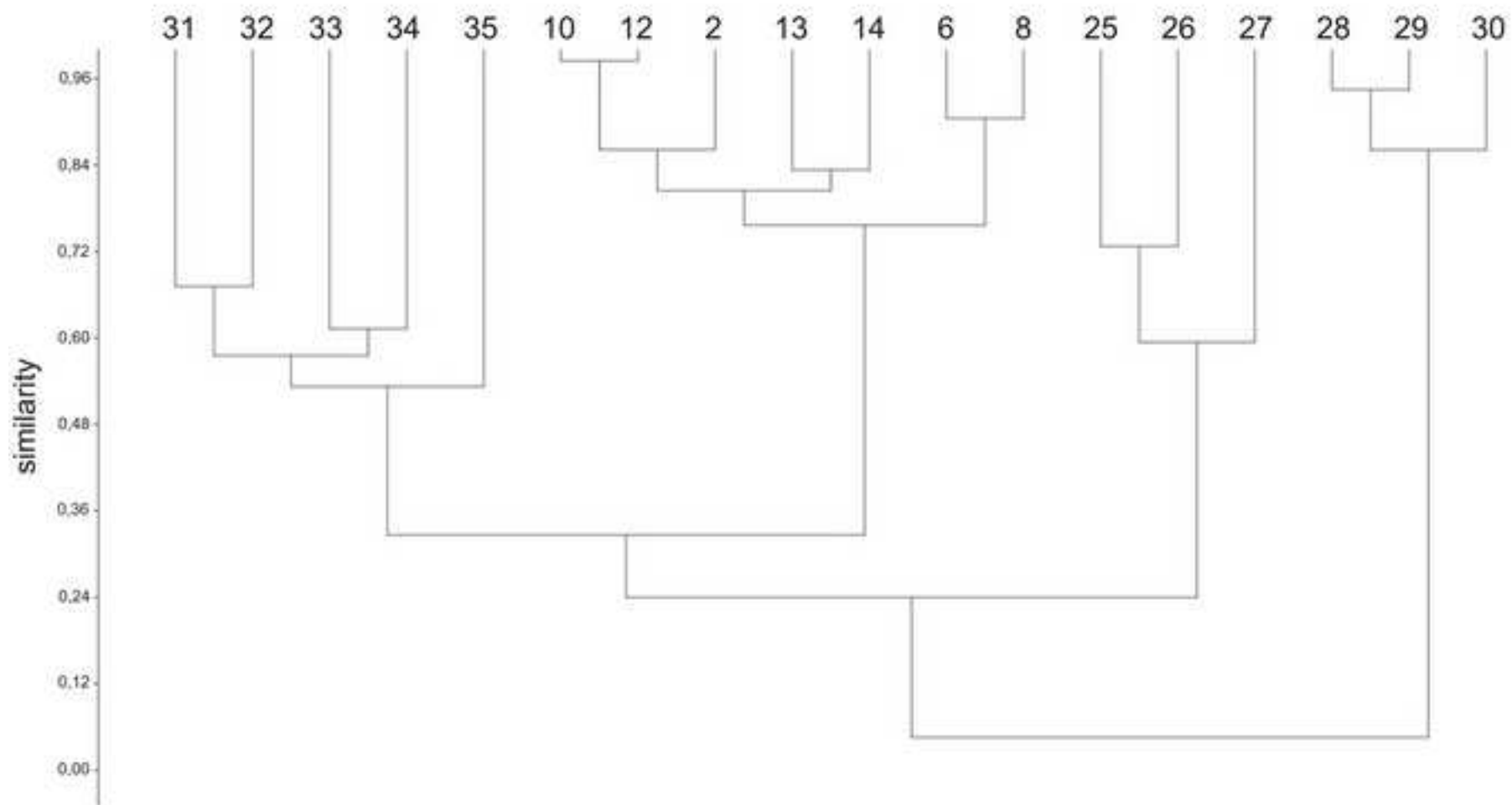


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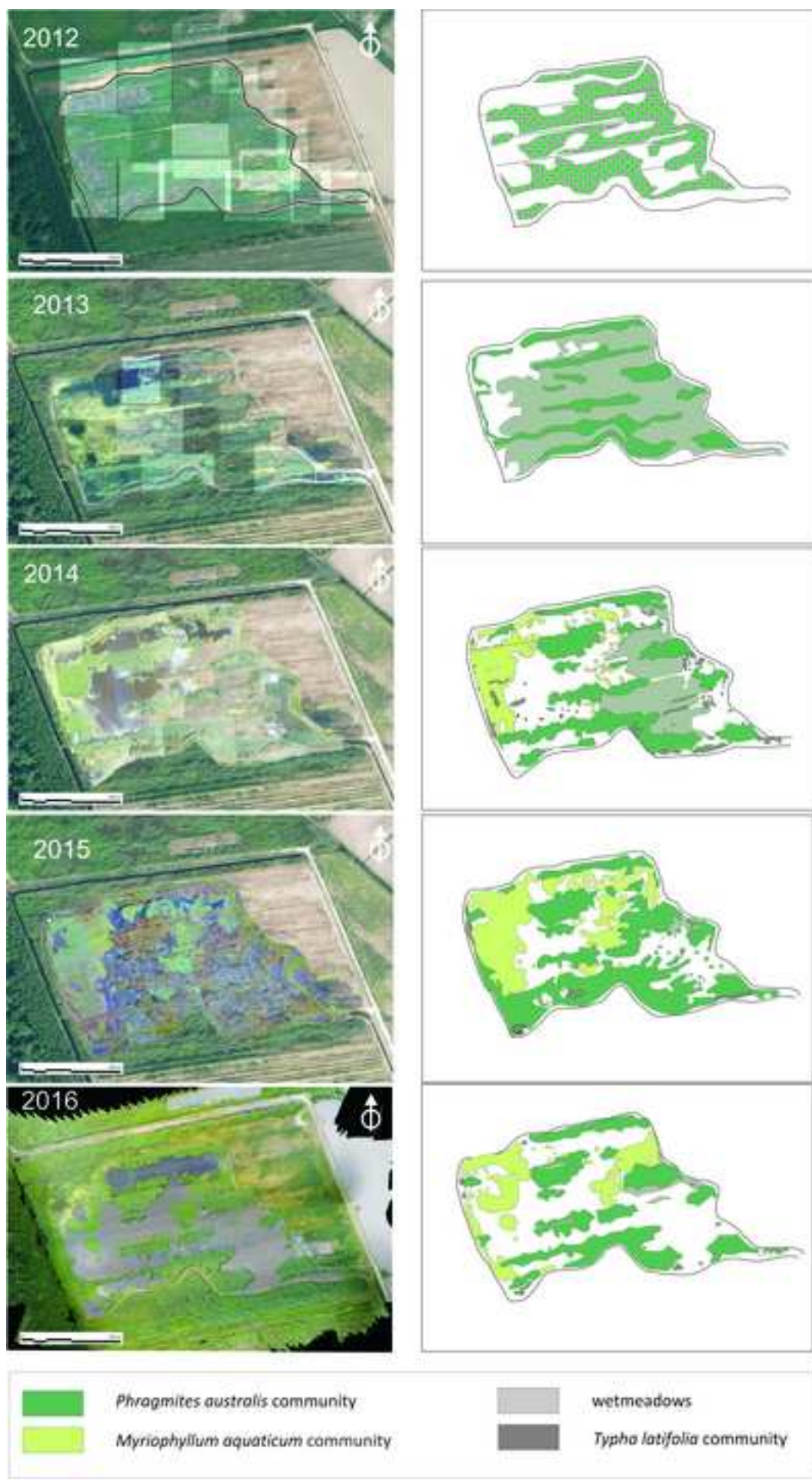
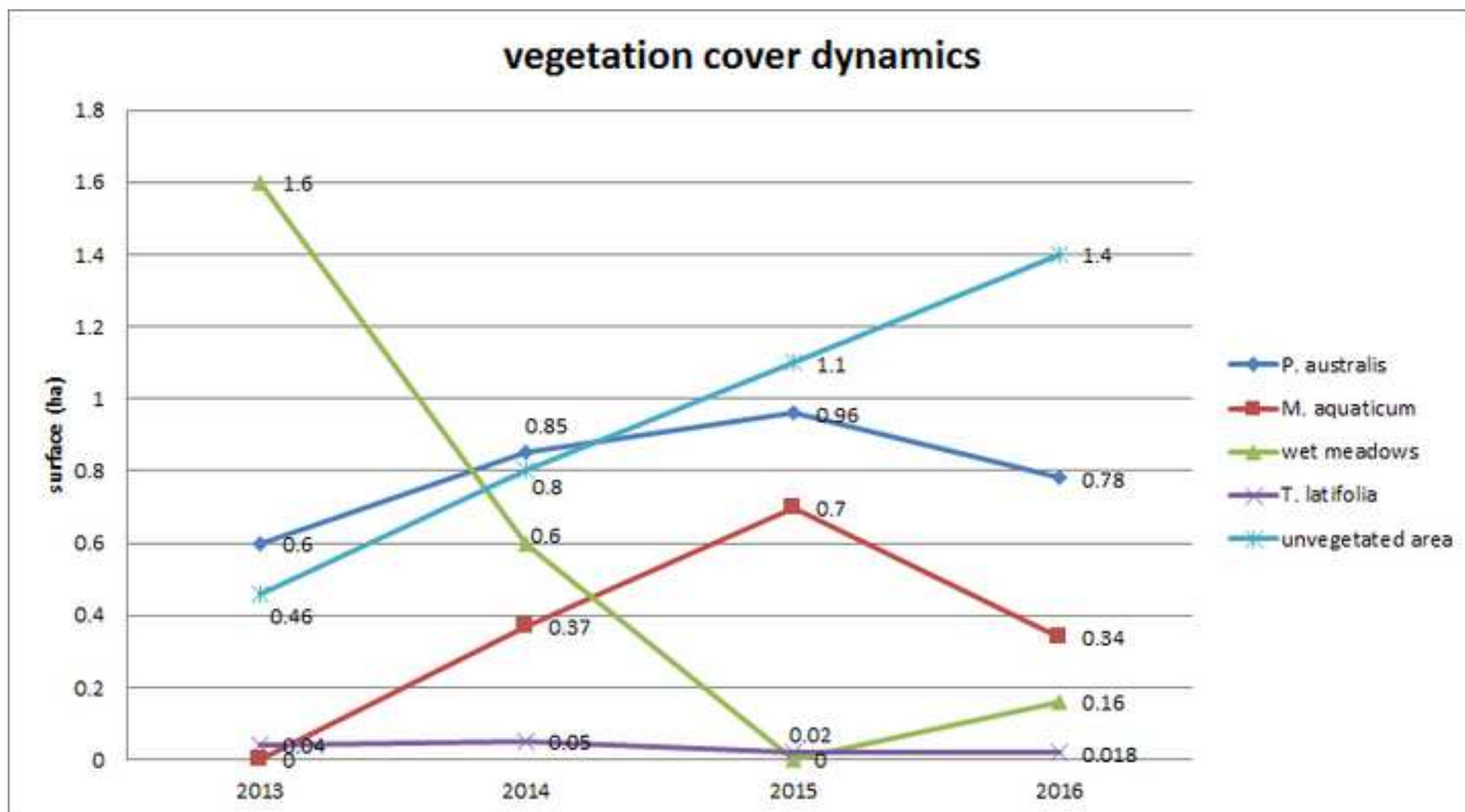


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Tab.1 Mean water table levels for the different seasons over the years of observation. The reported values (h in mm) were measured relative to the weir (~ 25 cm above the NWS bottom level) at the outlet of the system.* is used to report period with water flow interruption for operation activities.

Mean seasonal value: h (mm)				
	Winter (Dec-Feb)	Spring (Mar-May)	Summer (Jun-Aug)	Fall (Sep-Nov)
2013	50	55	38	65
2014	38*	11*	45	83
2015	76	66	76	70
2016	94	114	84	-

Tab.2 Table of the most representative phytosociological relevés (PH *Phragmites australis* community (Phragmitetum australis (Gams 1927) Schmale 1939); TY *Typha latifolia* community; MY *Myriophyllum aquaticum* community; WM Wet Meadows

(Surveys n. 2,6,8,25,26,31,32 were performed in June 2014; n. 10,12,27,28,29,33,34 were performed in June 2015; n. 13, 14,30,35 were performed in June 2016) (note: for index values, refer to the literature).

survey n°	2	6	8	10	12	13	14	25	26	27	28	29	30	31	32	33	34	35
Surface (sq)	25	25	25	25	25	25	25	9	9	4	60	100	100	25	25	25	25	25
Coverage (%)	100	100	100	100	100	100	100	80	80	100	80	80	100	50	70	80	100	100
Species n°	6	3	6	6	7	5	5	4	6	3	5	5	2	10	12	11	7	10
	PH						TY			MY			WM					
<i>Phragmites australis</i> (Cav.) Trin.	4	5	5	4	4	4	4	1	1	.	.	.	.	1	+	2	1	2
<i>Calystegia sepium</i> (L.) R.Br.	+	+	+	+	+	+	+	+	+	1	.	.	.	+	+	+	+	+
<i>Eupatorium cannabinum</i> L.	.	.	.	+	+	+	.	.	.	.	.	.	.	.	r	.	.	r
<i>Stachys palustris</i> L.	.	.	+	+	+	.	.	.	.	.	.	.	.	.	.	.	.	.
<i>Lythrum salicaria</i> L.	+	.	.	+	+	.	r	+	1	.	+	+	.	+	+	2	+	r
<i>Typha latifolia</i> L.	.	r	r	.	.	.	.	3	2	4	.	r	+	.	.	.	.	.
<i>Schoenoplectus tabernaemontani</i> (Gmel.) Palla	r	.	.	.	r	.	.	.	+	.	.	.	.	+	r	.	.	.
<i>Mentha aquatica</i> L.	.	.	r	.	.	r	.	.	.	.	.	.	.	.	.	.	.	.
<i>Iris pseudacorus</i> L.	1	.	.	+	+	.	.	.	.	.	.	.	.	.	r	.	r	+
<i>Oenanthe aquatica</i> L.	.	.	+	.	.	.	+	.	.	.	.	.	.	.	.	.	.	.
<i>Apium nodiflorum</i> (L.) Lag	.	.	.	.	.	.	.	.	1	+	.	.	.	.	.	.	.	.
<i>Myriophyllum aquaticum</i> (Vell.) Verdc.	.	.	.	.	.	.	.	.	.	.	5	5	5	.	.	.	.	.
<i>Juncus articulatus</i> L.	.	.	.	.	.	.	.	.	.	.	+	.	.	.	.	.	.	.
<i>Lemna minor</i> L.	.	.	.	.	.	.	.	.	.	.	+	+	.	.	.	.	.	.
<i>Echinochloa crus-galli</i> (L.) P. Beauv.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	1	+	3	2
<i>Poa trivialis</i> L.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	+	1	.
<i>Juncus effusus</i> L.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	+	.	r
<i>Juncus bufonius</i> L.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	+	+	+
<i>Carex otrubae</i> Podp	.	.	.	.	.	.	.	.	.	.	.	.	.	.	r	r	.	+
<i>Paspalum dilatatum</i> Poir.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	+	+	+	+
<i>Ranunculus sceleratus</i> L.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	+	+	.
<i>Ranunculus sardous</i> Crantz	.	.	.	.	.	.	.	.	.	.	.	.	.	.	+	+	+	.
<i>Samolus valerandi</i> L.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	+	.	.	.
<i>Epilobium hirsutum</i> L.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	+	+	.

Tab.3 - Results of ANOVA on the *P. australis* parameters. Within each factor, means in the same column followed by different letters are significantly different at $p < 0.05$ (Duncan test).

Treatments	Biomass (kg m ⁻²) d.m.	N content (%)	P content (%)
Subarea 1	4.77	1.96	0.16
Subarea 2	4.77	1.87	0.16
Subarea 3	5.75	2.03	0.19
Subarea 4	5.01	1.76	0.19
Subarea 5	3.15	1.55	0.14
Subarea 8	4.64	1.61	0.17
Subarea 9	6.44	1.77	0.18
	p = 0.3692	p = 0.4449	p = 0.5055

Tab.4 - Results of ANOVA on the *M. aquaticum* parameters. Within each factor, means in the same column followed by different letters are significantly different at $p < 0.05$ (Duncan test).

Treatments	Biomass (kg m ⁻²) d.m.	N content (%)	P content (%)
Subarea 6	0.91 b	2.20	0.44
Subarea 7	1.43 a	1.88	0.30
Subarea 10	0.80 b	2.05	0.30
	p = 0.0378	p = 0.1759	p = 0.0669