

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

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(Article begins on next page)

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

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8 **Highlights:**

- 9 1. Rewetting peaty soils, formerly drained for agricultural purposes, can contribute to increase  
10 the diversity of species in these ecosystems
- 11 2. The combined use of remote sensing and vegetation field surveys provides a snapshot at any  
12 given time of the surface colonized by the different plant communities and their  
13 development
- 14 3. *Phragmites australis* and *Myriophyllum aquaticum* can take up remarkable quantities of  
15 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. ( $4.94 \text{ kg m}^{-2}$  vs  $1.08 \text{ kg m}^{-2}$ ). *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 CO<sub>2</sub> equivalent ha<sup>-1</sup>y<sup>-1</sup> (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 NO<sub>3</sub><sup>-</sup> 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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2 consecutive management represent an environmental priority to face.  
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5 63 From literature, we can derive that there are different reasons leading to the change by moving from  
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7 64 the traditional drainage-based management of peatlands: stimulating the restoration of land portion  
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9 65 deteriorated from prolonged drainage (e.g. restoring) or recovery of the agricultural productivity of  
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11 66 the areas (e.g. paludiculture).  
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14 67 Regardless the aims behind the restoration, we can assume that to achieve the rehabilitation of at  
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17 68 least some of the functions supplied by these ecosystems, two main conditions have to be met i)  
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19 69 rewetting (e.g. constructing dams or filling in drainage ditches) and ii) reduction of trophic status  
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21 70 (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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23 71 al., 2014).  
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26 72 Both are not without side effects. Raising water level and flooding organic soils can lower the soil  
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28 73 nutrient availability (mainly released as ammonium), but can at the same time boost phosphorus  
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30 74 mobilization (Lamers et al., 2002; Meissner et al., 2008; Zak et al., 2004).  
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32 75  
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34 76 Top soil removal, i.e. the removal of the upper and most degraded peat layers responsible of the  
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36 77 higher mobilization of phosphorous during the rewetting phase (Zak and Gelbrecht, 2007; Zak et  
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38 78 al., 2017) causes the removal of the reproductive organs of plant species (seeds, stolons, rhizomes,  
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40 79 etc.) (Leps, 1999) delaying the time of re-naturation.  
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43 80 The case study reported in the present paper is linked to a project realized in Tuscany (IT), which  
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45 81 compares three different management strategies aimed to combine the peatland rewetting and the  
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47 82 water phyto-treating action.  
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51 83 In this paper, we focused on the Natural Wetland System (NWS). The first objective was to follow  
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53 84 the restoration process after rewetting of lowlands to evaluate the dynamics driven by the re-  
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55 85 established vegetation. According to literature, the ecological restoration perspective is highly  
56  
57 86 dependent on the zero-point condition before starting the restoration process (Klimkowska et al.,  
58  
59 87 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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289 within 5 years, Poschlod (1992) shows that in the case of peatland severely used for peat extraction  
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590 mostly monospecific stands of non-peat-forming species could develop even for 20 years after the  
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791 rewetting. Joosten (1995) even reports that in the cases of severe anthropogenic impact on the  
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1092 environment, it is not possible to observe any change within a human time perspective.

11  
1293 The second important research goal was to evaluate the capability of the NWS to work as phyto-  
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1594 treatment system thanks to the capability of plants to take up nutrients from waters proportionally to  
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1795 the biomass production and nutrient contents in the vegetative tissues.

## 19 2096 **2. Material and Methods**

### 21 22 2397 **2.1 Site description**

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2798 The study was carried out over 5 years (2011-2016) in Vecchiano, about 10 km from Pisa, Italy  
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2999 (43° 49' 59.5''N; 10° 19' 50.7'') in the Migliarino, San Rossore, Massaciuccoli Natural Park,  
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31  
32100 within a 15 ha experimental area (Fig.1a,b).

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34101 This site was used to compare the efficiency of three different strategies in treating the eutrophic  
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37102 drainage water coming from a cultivated sub-watershed within the reclamation district around the  
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39103 Massaciuccoli Lake. In this area, phosphorous has been recognized as the primary cause of the  
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42104 eutrophication and the losses of this nutrient from cultivated fields (dissolved + particulate  
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4405 fractions) are estimated in 2-4 kg ha<sup>-1</sup>y<sup>-1</sup> (Pensabene et al., 1997; Bonari et al., 2013).

45  
46106 The NWS was set up as natural rewetted area with a surface area of 2.7 ha and surrounded by small  
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49107 embankments built with the top soil (~ 10 cm) removed long the area's borders. Natural elevation  
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5108 changes within the NWS helped in creating zones with a different bottom height in order to promote  
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54109 the colonization from a large variety of plant species.

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56110 The soils of this experimental area has been classified as Histosol according to the USDA system  
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59111 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 ).  
6

118 The water level within the NWS was registered daily from December 2013 to August 2016. From  
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119 January 2013 to November 2013, the system was not equipped with a diver (CTD-Diver produced  
8  
120 by Schlumberger) for the water level measurement, thus manual measurements were performed  
9  
121 every 15 days (Tab.1).  
10

122 The analyses of treated waters confirmed their eutrophic status with average annual total nitrogen  
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123 content ranging from 7.14 mg/L to 8.13 mg/L, the average annual total phosphorus content ranging  
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124 from 0.24 to 1.07 mg/L. About the soluble forms, the average annual Soluble Reactive Phosphorus  
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125 (SRP) ranged between 0.15 and 0.22 mg/L, while the average annual nitrates content varied from  
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126 1.41 to 3.23 mg/L.  
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## 127 **2.2 Trial setup and vegetation analyses**

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128 The construction works lasted two years (2011 and 2012) and in January 2013 the phyto-treatment  
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129 system started to operate. The NWS's vegetation was periodically monitored from April 2013 up to  
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130 July 2016. Every year, in spring-summer, vegetation development and phytocenotic diversity were  
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131 surveyed using the Braun-Blanquet method (Braun-Blanquet, 1979). 30 Relevés were performed on  
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132 surfaces varying from 4 to 100 m<sup>2</sup> depending on the typology of the plant community. The used  
21  
133 nomenclature of the plants accords to Pignatti (1982) and Conti et al. (2005).  
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134 A multivariate analysis procedure using syntax software (Podani, 2001) was carried out for data in  
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135 vegetation surveys. The matrix of 48 species x 18 surveys was analysed according to UPGMA  
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136 cluster algorithm analysis, applying the coefficient of similarity of Bray-Curtis. During the  
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137 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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3452 sampling plots were chosen on the basis of the vegetation map assembled after the flight of June  
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3953 representative plots to use for the sample collection. In particular, we identified 7 homogenous  
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4654 sampling areas for *Phragmites australis* (Cav.) Trin. ex Steud. and 3 for *Myriophyllum aquaticum*  
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5155 (Vell) Verd.(Fig. 2). Within each of these areas, we took 3 samples using a metal frame with an  
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6156 inner area of 1 m<sup>2</sup>. The biomass of *P. australis* was harvested above the water surface level, while  
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7157 in the case of *M. aquaticum* we took both the aerial and submerged parts (emergent shoots, stolons  
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8158 and submersed shoots), that is almost the whole plant biomass (Sytsma and Anderson, 1993). All  
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9159 sampling was done from a boat to minimize disturbance of the ecosystem.  
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10160 For the determination of dry mass, samples were dried at 60 °C until reaching constant weight. To  
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11161 determine the composition of biomass, samples were finely milled with a Fritsch Pulverisette 14.  
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12162 Nitrogen and Carbon concentration were measured with a CHNS Analyzer (Vario EL III -  
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13163 Elementar Analysensysteme Hanau Germany) through gas chromatography after dry combustion at  
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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 m<sup>2</sup>. 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<sup>-1</sup>) 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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192 3).

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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.

### 23 24 199 **3.2 Photointerpretation and vegetation mapping**

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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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49  
50 the covered surface between 2013 and 2015 (from 0.04 ha to 0.70 ha), whereas it has been more

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53 than halved in the last year (0.34 ha). The development of the *P. australis* showed the shortest

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56 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  
9  
218 were normally distributed ( $W = 0.967$  and  $W = 963$  for *P. Australis* and *M. aquaticum*,  
11  
219 respectively) and their variances were homogeneous ( $p > \chi^2 = 0.465$  and  $p > \chi^2 = 0.295$  for *P.*  
14  
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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19

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  $4.94 \pm 1.67$  (standard deviation)  $\text{kg m}^{-2}$  d. m. (dry matter) and the values from the different sub-  
26  
225 areas ranged from  $3.15 \text{ kg m}^{-2}$  d. m. (sub-area 4) to  $6.44 \text{ kg m}^{-2}$  d. m. (sub-area n.9).  
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29

226 *M. aquaticum* was less productive than *P. australis* with a mean production of  $1.05 \pm 0.35$  (s.d.)  $\text{kg}$   
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227  $\text{m}^{-2}$  d. m. (weighted on the surface of each sub-areas). The sub-area 7 ( $1.43 \text{ kg m}^{-2}$  d.m.) was  
33  
228 significantly more productive than the other two (sub-areas 6 and 10) that were statistically  
36  
229 equivalent between them ( $0.80$  and  $0.91 \text{ kg m}^{-2}$  d. m., respectively).  
38  
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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  
43  
232 total surface occupied by *P. australis*, whereas we used the means of the sub-area 7 and the sub-  
45  
233 areas 6 and 10 multiplied by the respective surface values, in the in the case of *M. aquaticum*.  
48

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*  
53  
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  
56  
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  
1  
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.)  
10  
11  
1244 in *M. aquaticum*. The mean concentrations of the two species were quite close in the case of  
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14  
245 nitrogen, although *M. aquaticum* showed again the higher values with  $2.04\% \pm 0.29$  (s.d.) against  
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16  
246  $1.79\% \pm 0.21$  (s.d.) of *P. australis*.  
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18

19  
247 The nutrients taken up per unit area were equal to  $882 \text{ kg ha}^{-1}$  of N and  $84 \text{ kg ha}^{-1}$  of P for *P.*  
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21  
248 *australis* and  $220 \text{ kg ha}^{-1}$  of N and  $38 \text{ kg ha}^{-1}$  of P for *M. aquaticum*. From these data, we can derive  
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23  
249 that the total nitrogen taken up from the spontaneous vegetation growing within the NWS was 761  
24  
25  
250 kg, of which 688 kg taken up from *P. australis* (90%) and the remaining 73 kg taken up from *M.*  
26  
27  
28  
251 *aquaticum* (10%).  
29  
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31  
252 About phosphorus, *P. australis* contributed to take up 65 kg (83% of the total) while *M. aquaticum*  
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33  
253 to 13 kg (17% of the total).  
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## 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65

#### 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  
1  
264 showed a quick renaturation process, as evidenced by the wide surface covered by the different  
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4  
265 plant communities.  
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6  
266 The spatial distribution of the vegetation species within the area showed the prevalence of the *T.*  
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9  
267 *latifolia* on the borders or in the strips surrounding the central nucleus of NWS system colonized by  
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11  
1268 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  
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1270 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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21  
222 long time and limit the development of other plants, which are not helophytes or are not provided  
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24  
273 with aerenchyma.  
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26  
274 This behavior seemed to be proved by the wet meadows development that was largely widespread  
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28  
2275 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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31  
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.  
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41  
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.  
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59  
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  
8  
293 sensing data, was particularly useful for the identification of the vegetation dynamics following a  
10  
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<sup>-2</sup> d.m.) was the effect of a series of  
30  
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  
35  
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<sup>-2</sup> d. m. at the peak of productivity in a nutrient-  
42  
43307 enriched swamp in inland Australia. Gopal and Sharma (1982) reported production ranging from  
44  
454608 7.50 to 9.30 kg m<sup>-2</sup> 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<sup>-2</sup> d. m. in Egypt (Burullus Lake), data which are  
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50  
5110 quite similar to our average production.  
52

53311 In conditions of limited nutrient availability, the production of *P. australis* are definitely lower as  
54  
555612 reported in literature: Aseada et al. (2002) up to 1.03 kg m<sup>-2</sup> d. m. in Austria; Karunaratne et al.  
57  
58313 (2003) 1.98 kg m<sup>-2</sup> d. m. in Japan and Aseada et al. (2006) 0.69 kg m<sup>-2</sup> d. m. in Japan.  
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314 Also for *Myriophyllum aquaticum*, mentioned in literature as parrot feather, many studies confirmed  
1  
315 a positive correlation between relative growth rate and nutrient availability (Hussner et al., 2008).  
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4  
316 However the average yield we registered (1.08 kg m<sup>-2</sup> d. m.) was lower than that reported by  
6  
317 Shybayama (1988) (2.80 kg m<sup>-2</sup> d. m., assuming a fresh weight/dry weight ratio equal to 0.21) or by  
8  
318 Monteiro and Moreira (1990) (about 4.60 kg m<sup>-2</sup> 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<sup>-2</sup> 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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41  
331 (Vymazal, 2007).  
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43  
332 In our study, the mean amount of nutrients removed were high for *P. australis* (882 kg N ha<sup>-1</sup> and  
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46  
333 84 kg P ha<sup>-1</sup>) and although lower, as well remarkable also for *M. aquaticum* (~220 kg N ha<sup>-1</sup> and  
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48  
334 ~38 kg P ha<sup>-1</sup>).  
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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<sup>-1</sup> y<sup>-1</sup> and ~ 130 kg P ha<sup>-1</sup> y<sup>-1</sup>, 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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4  
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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9  
343 This value was also confirmed by results published by Giannini et al. (2016, 2017).  
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344 Although the fate of these nutrients is uncertain, it is presumable that they remain immobilized  
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345 within the organic compounds for long time because of the anoxic condition that the plant residues  
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346 found on the NWS's bottom when they are not undergone to a chemical-physical stabilization  
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347 through peat-forming process. Thus, we should add to the amount of nutrient removed by NWS  
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348 plants also the nutrients that has been taken up in the previous years and translocated in the plant  
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349 portions left on the NWS bottom.  
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26  
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 4<sup>th</sup> 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.  
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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.  
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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.  
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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<sup>-2</sup> d.m. for the PCS (unpublished data) versus 4.94 kg m<sup>-2</sup>  
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36  
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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45  
383 impaired convective ventilation and hypoxia on the basal part of the reed stands (Rolletschek et al.,  
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48  
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  
6  
392 well-balanced harvest strategy by mowing *P. australis* every two years during summertime, after an  
8  
393 initial phase of 4-5 unharvested years. In this way, we can favor the plant settlement without  
10  
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  
14  
396 harvesting (at least annually) (Nuttall, 1985) and we can partially repeat the considerations already  
16  
397 expressed for *P. australis*.

398 However, this type of management can alter the renaturation process and preclude the possibility  
22  
399 for the NWS to reach the climax conditions. Moreover, it is not to neglect that the deposit of the  
25  
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  
30  
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,  
37  
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  
42  
407 some floristic association typical of the surrounding palustrine areas. This fact confirmed that the  
43  
408 status of peatlands was not as degraded as to prevent the spontaneous vegetation recolonization of  
47  
409 the rewetted areas.

410 Although our experimental area (NWS) was not so widespread to be considered representative of  
52  
411 the whole Massaciuccoli Lake catchment, was reasonable suppose that the main plant communities  
54  
412 and associations able to colonize rewetted peatlands are those identified within the experimental  
57  
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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6  
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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19  
422 the management of the harvest operations (necessity of draining area or use of machines able to  
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21  
423 work in flooded conditions) and cause disturbance to the biota.  
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24  
424 For this reason, the management of NWS has to find a compromise able to meet different needs  
25  
26  
425 (multifunctional management).  
27

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38  
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44  
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47

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49  
50  
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55

## 536 **Figure captions**

56  
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437 **Fig.1** (a) Aerial view of the Massaciuccoli Lake catchment (Tuscany, IT) and (b) zooming on the  
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60  
438 experimental area.  
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439 **Fig.2** Aerial picture of the Natural Wetland System (NWS) with the location of the homogenous  
1  
440 units identified for sampling. Areas n. 1, 2, 3, 4, 5, 8 and 9 are of *P. australis* (with sampling areas  
3  
441 marked in orange )while areas n. 6, 7 and 10 are of *M. aquaticum* (with sampling areas marked in  
4  
6  
442 red).

9  
443 **Fig.3** Dendrogram resulting from the cluster analysis of the relevès performed during the  
10  
11 observation period. The numbers reported are referred to the relevès listed in Tab.2.  
12  
13

14  
445 **Fig.4** The diachronic mosaic of the vegetation succession of the NWS from 2012 to 2016. On left  
15  
16 hand, the reconstruction from the ortophotos; on right hand, the sketch reporting the surface covered  
17  
18 by each community year by year. The analysis reported is referred only to summer flights.  
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448 **Fig. 5** Fluctuation of the cover values reached by different communities from 2013 to 2016.  
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#### 449 **Table captions**

27  
28  
450 **Tab.1** Mean water table levels for the different seasons over the years of observation. The reported  
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30 values (h in mm) were measured relative to the weir at the outlet of the system.\* is used to report  
31  
451 period with water flow interruption for operation activities.  
32  
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34  
452

35  
36  
453 **Tab.2** Table of the most representative phytosociological relevés (PH Phragmites australis  
37  
38 community (Phragmitetum australis (Gams 1927) Schmale 1939); TY Typha latifolia community;  
39  
40 MY Myriophyllum aquaticum community; WM Wet Meadows  
41  
455 (Surveys n. 2,6,8,25,26,31,32 were performed in June 2014; n. 10, 12,27,28,29,33,34 were  
42  
43 performed in June 2015; n. 13, 14,30,35 were performed in June 2016) (note: for index values, refer  
44  
45 to the literature).  
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459 **Tab.3** Results of ANOVA on the *P. australis* parameters. Within each factor, means in the same  
52  
53 column followed by different letters are significantly different at  $p < 0.05$  (Duncan test).  
54  
55

56  
461 **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

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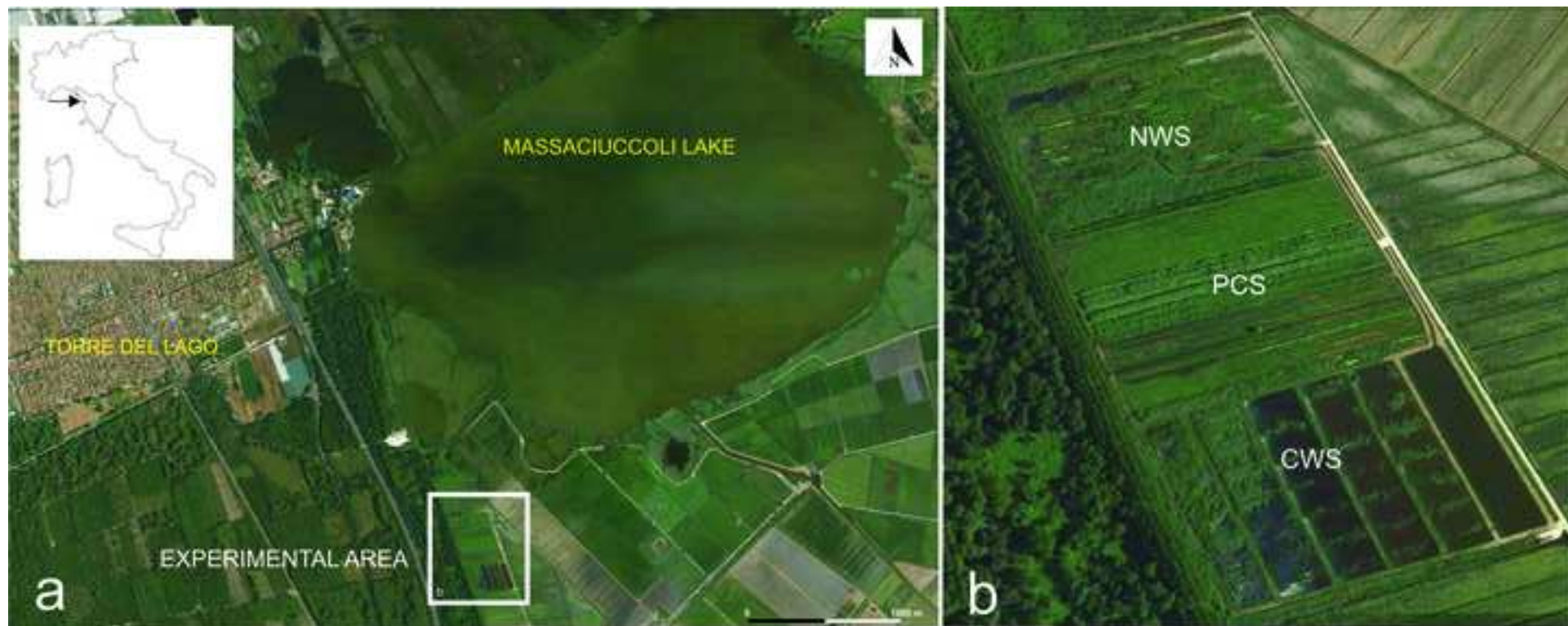


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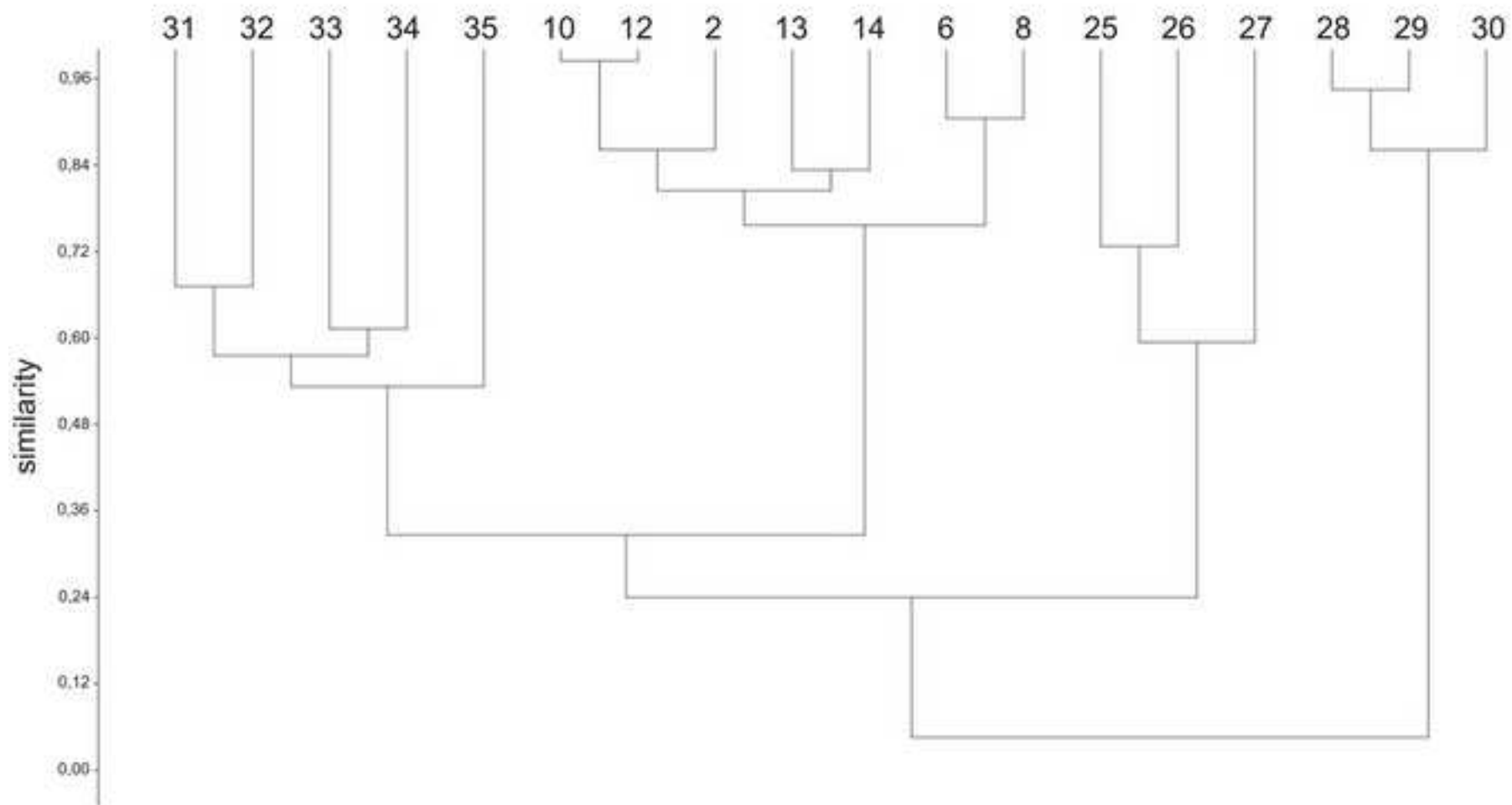


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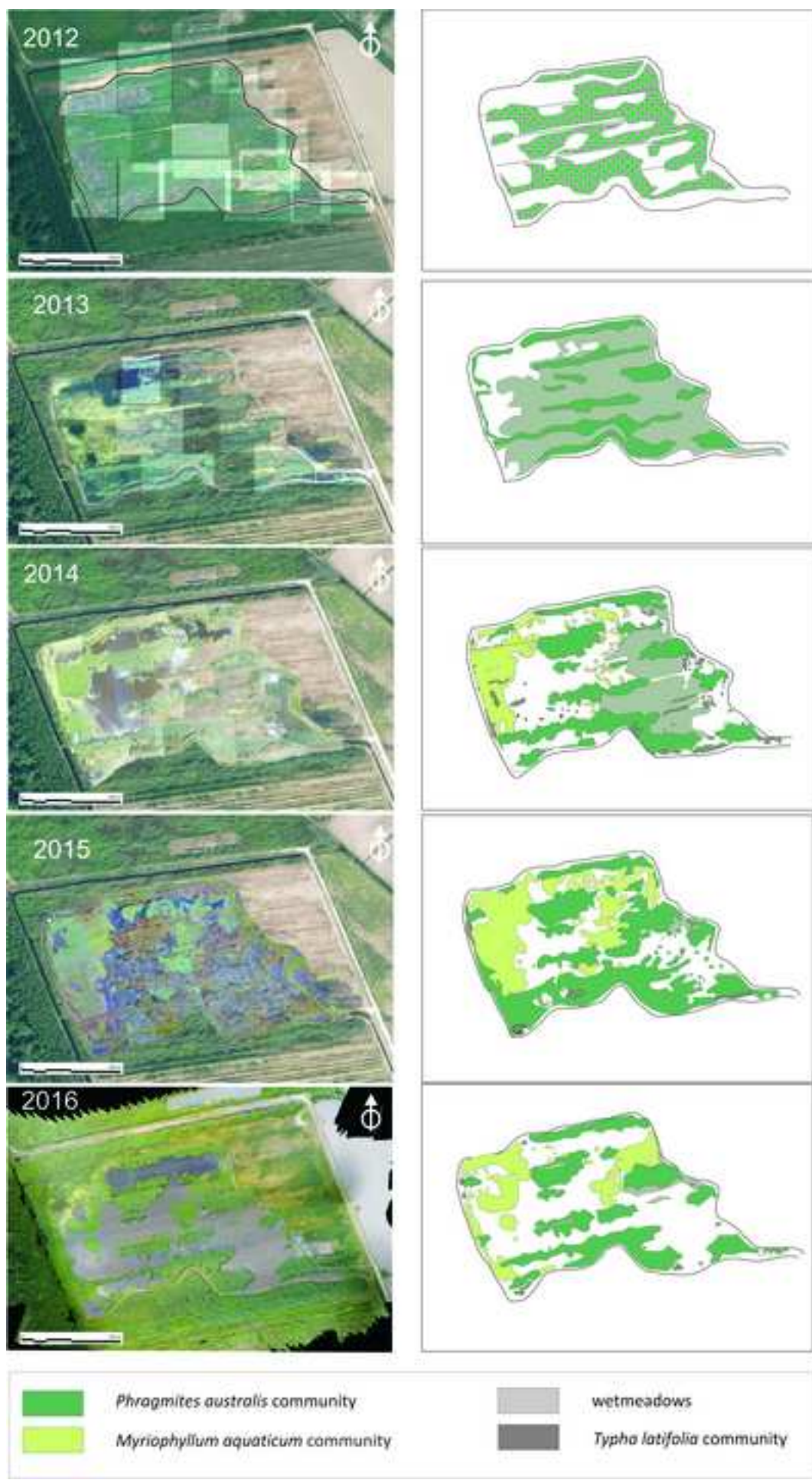
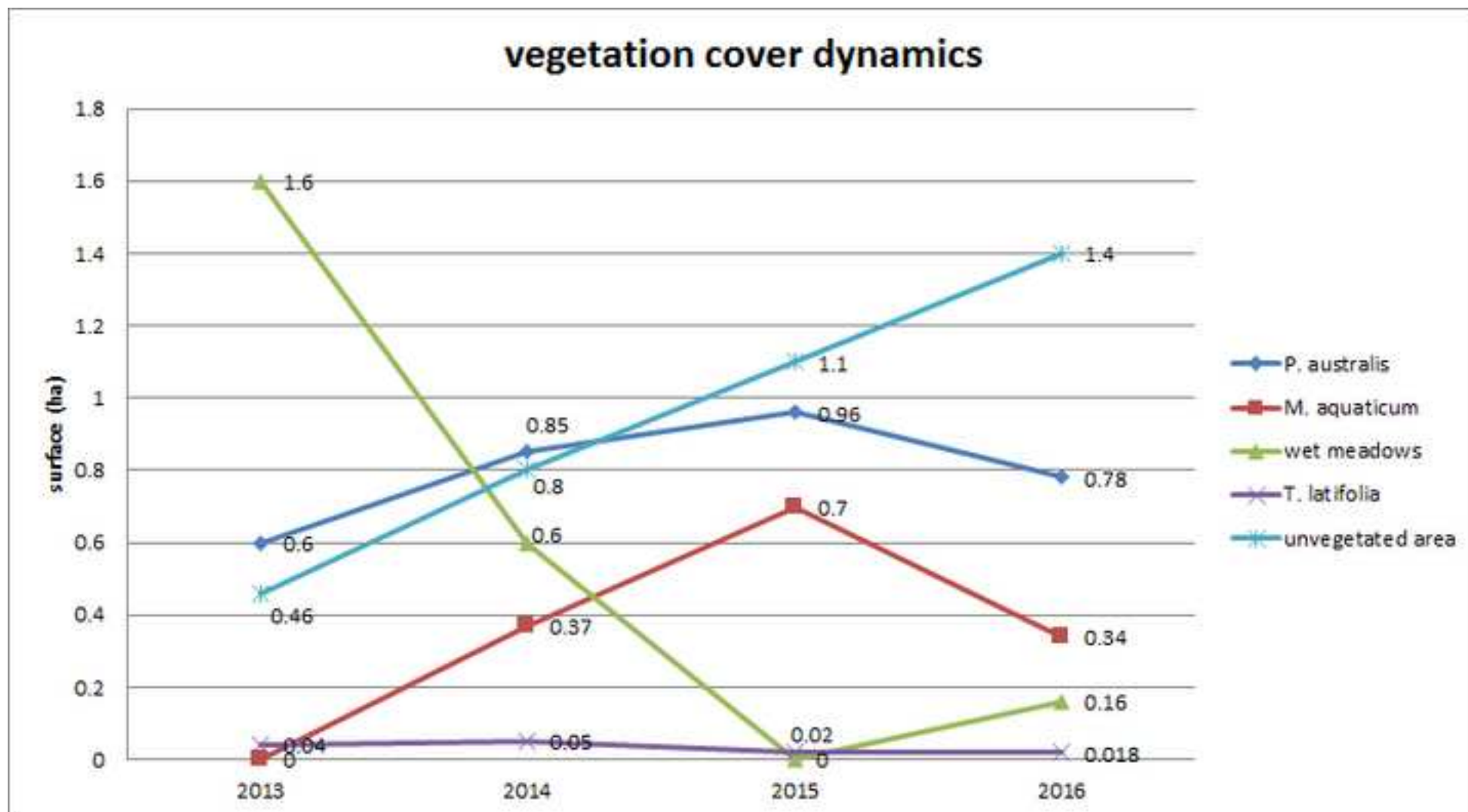


Figure 5  
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**Tab.1** Mean water table levels for the different seasons over the years of observation. The reported values (h in mm) were measured relative to the weir (~ 25 cm above the NWS bottom level) at the outlet of the system.\* is used to report 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.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 <sup>-2</sup> ) 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 <sup>-2</sup> ) 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