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Aquatic Plant-Mediated Phosphorus Migration in Lake Agmon-Hula, Israel

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Abstract

The drainage of the Hula wetlands and old "Lake Hula" was completed in the late 1950s. A significant area of land use was converted from its natural habitat to agricultural cultivation. Nevertheless, soil properties deteriorated; consequently, 40 years later, a land reclamation project was completed. A significant part of the reclamation project was the creation of a new shallow Lake Agmon-Hula (LAH). This shallow lake was a key component of the reclamation project, aimed at boosting tourism in the valley. Immediately after water filled the LAH, the adjacent land was invaded by both natural and reintroduced plant species. A follow-up program to monitor individual species and total biomass distribution of submerged, emerged, and floating plants, along with their TP and TN content, was carried out routinely, accompanied by assessments of inflow and outflow (effluent) phosphorus and nitrogen sources in the LAH. The overwhelming presence of nitrogen and the limited availability of phosphorus for rooted plant uptake were concluded. Considering Liebig's law, which states that plant growth is dictated by the scarcest resource, a contrasting result was found. The uptake of phosphorus, as the limiting factor, is preferred during biomass onset development, whereas it is transferred into LAH waters (measured as effluent at Station 49) later on during the degradation of biomass. The limited nutrient is the most influential factor in enhancing its concentration in lake water through involvement in vegetation biomass dynamics.

Keywords

Agmon, Hula, Aquatic Vegetation, TN, TP, TN/TP Ratio

1. Introduction

Lake Agmon Hula (LAH) is a newly created wetland ecosystem located in the Hula Valley. The Hula Valley is part of the northern section of the Great Syrian-African

Rift Valley. Until 1957, the Hula Valley was covered by swamps and the old Lake Hula. Anthropogenic intervention completed the drainage of the Hula Valley, and from 1958 onward, the land of the Hula Valley was converted to agricultural development. The objectives of Lake Agmon's creation aimed at three achievements: 1) becoming part of a reconstructed hydrological system to remove pollutants from Lake Kinneret's external loads; 2) creating a plant cover and establishing a bird-attracting, touristic wetland site; 3) serving as a hydrological device for managing agricultural irrigation systems. During the 1980s, it was recognized that agricultural development required reclamation. Inappropriate irrigation technologies and agricultural practices deteriorated soil properties and caused surface subsidence, which threatened Kinneret water quality due to pollutant migration. This prompted the implementation of a reclamation project, the "Hula Project," which included the construction of Lake Agmon. The water filling of Lake Agmon-Hula was carried out during the summer of 1994, creating a water body with the following dimensions: volume—0.44 × 10^6 m^3, surface area—110 ha, and mean depth—0.4 m. The territory of the Hula Project, which included Lake Agmon-Hula, was subject to monitoring and research aimed at evaluating an optimal model of operation. The optimized management model for Lake Agmon considered the following objectives: improvement of irrigation water supply, maintenance of an increased groundwater table (GWT) to ensure appropriate moisture for the peat soil, and the establishment of floral and faunal biodiversity that emphasized stop-over and night roosting for aquatic, semi-aquatic, and terrestrial birds, as well as their nesting activity. Attention was given to monitoring the biomass and nutrient content distributions of aquatic vegetation. This paper focuses on two major issues: nutrient dynamics and the role of biomass and N & P content of macrophytic vegetation within the lake ecosystem. Ecosystem fertility depends on nutrient and water availability, which are the drivers of system production. The maintenance of the Lake Agmon-Hula ecosystem aims to protect biodiversity, enhance species richness, support beneficial agriculture, and promote recreation and eco-tourism. Appropriate management includes both natural processes without human intervention and combined anthropogenic involvement. Hydrological extremism resulting from climate change ranges between water scarcity and abundance.

Three years after water filling in LAH, a special issue of Wetlands Ecology and Management Journal entitled "Destruction and Creation of Wetlands in Northern Israel" [1] was published. The three-year record of Lake Agmon's environmental characteristics of LAH was documented: phytoplankton, metaplankton, geochemical properties, ichthyofauna, avifauna, climatological and hydrological conditions, and macrophytic vegetation were documented [2]. Sulfate, carbonate, nitrate, and iron sulfide present in the bottom sediments and pore-water geochemical properties were evaluated [3] [4]. Although phosphorus, nitrogen, and the N/P ratio in relation to vegetation growth dynamics were not studied, the impact of sulfide formation on the growth of Typha domingensis was considered [3]-[5]. Despite the high concentration of sulfate and iron, and scarce events of pore water anoxic conditions, the formation of small concentrations of toxic sulfide (6 - 8 μM) was recorded [3]-[5]. Nevertheless, the toxic impact of sulfide on aquatic vascular plants was widely documented, and lethal concentrations were defined as 10^2 - 10^3 times higher than documented and could not be a significant reason for the Typha collapse in LAH. Available P limitation was documented as a lethal factor for Typha domingensis in LAH [6]. An experimental study of N, P, and N/P mass ratio uptake by Cyperus papyrus and Typha domingensis cultured on Hula Peat soil substrate confirmed that the documented low concentration of sulfide is not lethal [7]. The intensive transfer of P from bottom sediments into the water of LAH through rooted submerged and emerged vascular plants was widely considered [6] [8]-[10]. Surveys of submerged and emerged vascular plants were carried out four times a year during 1997-2004. A detailed survey was conducted in August 2004 [11] [12]. The objective of this paper is to incorporate supportive information about the impact of aquatic vegetation dynamics on the availability of phosphorus and nitrogen within the management design.

2. Material and Methods

2.1. Study Site (Figure 1)

The study is of the Hula Project territory, including indication of open canals, reconstructed Jordan rout, Lake Agmon-Hula (LAH) and ground water sampling bore holes.

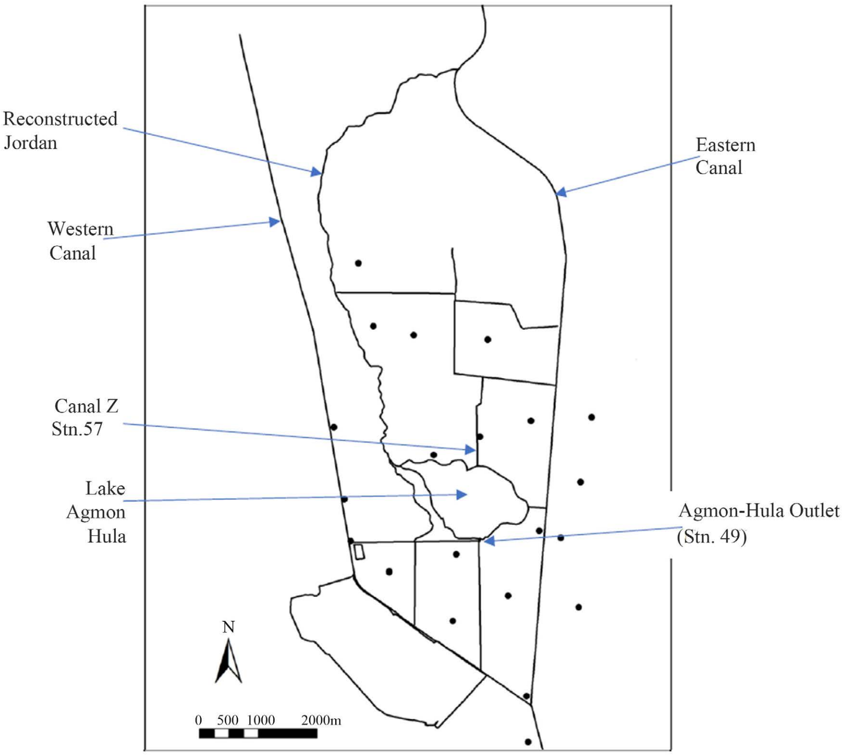

Figure 1. Chart map of the Hula project territory. water channels and other ecosystem compartments are arrowed; black dots are sampling borehole drill locations.

2.2. Plant Distribution Sampling

The establishment of colonized plant species in LAH and adjacent areas between 1994 and 1996 was carried out through four 30 - 250 m length transects directed perpendicularly from the shoreline towards the central zone of LAH. Along each transect, 4 - 7 quadrants (22 total) of the bottom surface were defined and plant species composition and phenological (cyclical plant cover dynamics) characteristics were documented in each. The plant distributional cover in LAH between 1997 and 2004 was carried out by a distributional density definition of a 46 "Polygons" network, where each represents a bottom surface area of 19.6×10^2 m^2 (~2 ha). Aerial boundaries were marked by sticks assigned by GPS, Magellan 4000 [11] for mapping outlines through GIS, ArcView. A 1 m^3 volume cage made of a metal frame with fiberglass walls was sunk underwater, touching the bottom layer. All plants within the cage were collected [11].

Sampling frequency was strictly dependent on budget availability and therefore carried out 1 - 4 times a year during the seasonal onset and offset periodical growth and degradation of the submerged vegetation. Mapping of the "polygon" aerial distribution was aimed at optimal cover of the bottom variety of LAH sediment types.

After evaporated dewatering of sorted plant samples, the material was kept shortly under 4˚C before grounding preparation for chemical analysis.

2.3. Biomass (WW, DW) and Nutrient Composition

Collected plant matter was placed onto a metal mesh for excess water removal, species sorting, and wet weight (WW) was measured. The dry weight measure was taken after oven drying at 56˚C for 48 hours. Dry plant matter was ground into powder and 2 g were sub-samples for Nitrogen (Nesler-Nitrogen Analysis), and Phosphorus (Ascorbic acid method) analysis [11].

2.4. Surface Water Sampling

Runoff waters were sampled weekly at 3 stations:

Station 49: The exit location of the LAH effluents representing the entire LAH water quality; Station 57: Entrance location (Canal Z) of Peat soil drained waters into LAH; TN and TP analysis were carried out in Migal-Analytical [1].

3. Results

Species list of submerged and emerged rooted vascular plants in LAH recorded in Hula Project annual reports (1997-2004): *Potamogeton berchtoldii, P. filiformis, P. pectinatus, P. trichoides, P. nodosus P. crispus, Najas minor, N. delilei, Phragmites australis, Typha domingensis, Cyperus sp. Ceratophyllum submersum, Ludwigia stolonifera, Paspalum paspalodes.* Filamentous and Charophyte algae and the floating plant of *Lemna minor* were recorded as well [11] (**Table 1** and **Table 2**).

Table 1. Summary of total DW biomass (g/m²) and TN, and TP (g/m²) content (mg/m²) within submerged and emerged vegetation in Lake Agmon-Hula (LAH) as documented during August-September 2004. The bottom surface area of LAH is: 1100 × 10^3 m².

Plant	Total DW Biomass (g/m²)	TP (mg/m²)	TN (mg/m²)	TN/TP Mass Ratio
Filamentous algae	0.539	0.1	11	110
Ludvigia stolonifera	80	211	2119	10.0
Potamogeton nodosus	3.1	9	98	10.9
Najas minor	0.555	1	14	14.0
Paspalum paspalodes	37.1	119	823	6.9
Ceratophyllum submersum	25.2	70	730	19.4
Cyperus sp	0.455	1	6	6.0
Phragmites australis	341.3	379	4629	12.2
Typha domingensis	146.9	178	1119	6.3
Total	635.1	968	9549	9.9

Table 2. The annual (1997-2004) DW Biomass (ton) peaks and their nutrient (TP, TN) contents (ton) of submerged and emerged vegetation in Lake Agmon-Hula (LAH). The TN/TP Mass Ratio is given. Several (3 - 6) dominant plant species were recorded during 1997-1999 and 2001-2004, whilst only one most common species (*Typha domingensis*) was documented during the peak of August 2000. The lowest TN/TP mass ratio (7.3) within plant tissues was recorded when *Typha domingensis* was dominant.

Year	Month	DW Biomass (ton)	TP (ton)	TN (ton)	TN/TP Mass Ratio
1997	June	268	0.9	7.4	8.2
1998	July	213	0.7	6.3	9.0
1999	August	432	0.8	7.8	9.8
2000	August	344	0.9	6.6	7.3
2001	July	740	1.2	9.8	8.2
2002	September	817	1.14	9.75	8.6
2003	August	140	0.29	2.66	9.2
2004	August	698	1.07	10.5	9.8

Table 3. Averaged Total Phosphorus (TP) and Total Nitrogen (TN) of the vegetation tissue content (mgTP/m², mgTN/m²) and TN/TP mass ratio of submerged and emerged plants which covered northern, central and southern zones of Lake Agmon-Hula bottom documented in August 2004.

TN	TP	Lake Zone	TN/TP
9955	617	Center	16.1
6013	944	North	6.4
6742	567	South	11.9

Lake Agmon-Hula's surface area was divided by 46 "Polygons," which were sorted by three regions: 16, 17, and 12 of them covered the Southern, Central, and Northern Lake zones, respectively. From 1997 through 2004, the TN/TP mass ratio of peak DW biomass of submerged and merged vegetation in LAH indicates values that range between 8.2 - 9.8, which emphasizes conditions of intensive P incorporation in relation to N consumption. The averaged Phosphorus and Nitrogen distributional content (mg/m^2) within the plant tissue submerged and emerged in August 2004 in Lake Agmon-Hula are given in **Table 3**.

The TP and TN content per surface area (mg/m^2 and g/m^2) within submerged and emerged plant species tissue was calculated considering distribution and chemical composition and polygon surface area documented during August 2004 (**Table 4**) (Kaplan 2004). Lower and higher Phosphorus in relation to Nitrogen consumption in the central-southern and northern lake regions, respectively, are consequently suggested.

Table 4. TP TN (mg/m^2), and total DW biomass, averages of submerged and emerged plant species and TN/TP mass ratio, documented in LAH, August 2004 [11].

Plant	DW Biomass (g/m^2)	mgTP/m^2	mgTN/m^2	TN/TP mass ratio
Ceratophyllum demersum	226	1196	7125	6
Paspalum paspalodes	601	1923	13000	6.8
Typha domingensis	483	385	2738	7.1
Ludwigia stolonifera	337	545	5361	9.8
Potamogeton nodosus	14	39	432	11.1
Najas minor	4	9	106	11.8
Phragmites australis	1236	1555	22353	14.4
Filamentous algae	9	12	180	15
Cyperus sp.	11	27	740	27.4

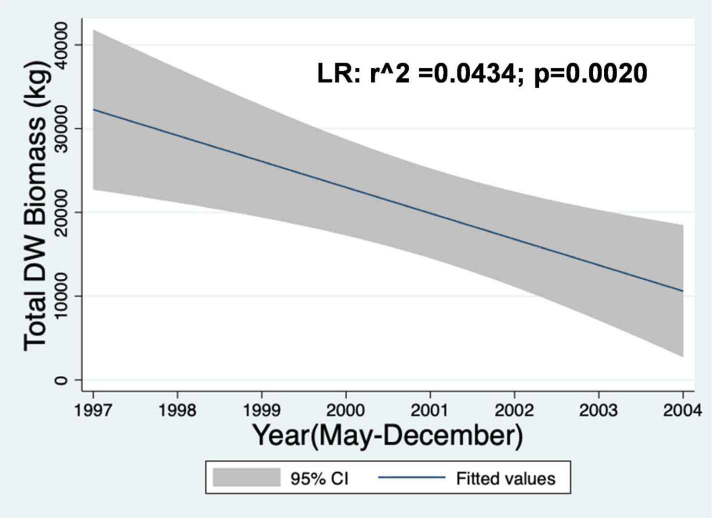

Figure 2. Annual (1997-2004) temporal changes of seasonal (May-December) total DW biomass (kg) of submerged and emerged vegetation in Lake Agmon-Hula (LAH).

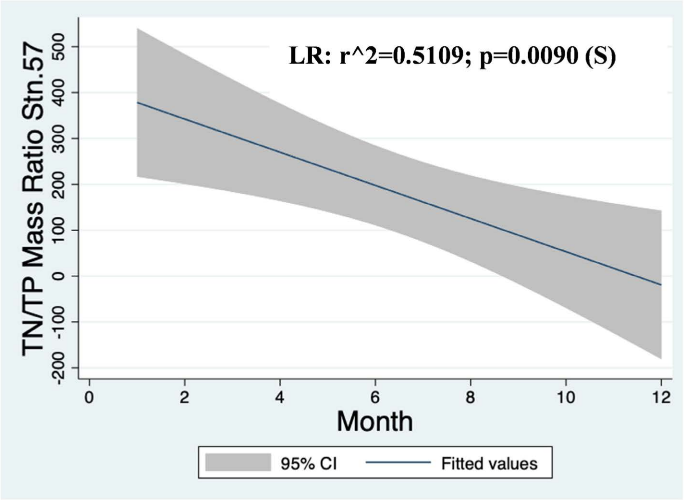

Figure 3. Monthly means of TN/TP mass ratio measured in Station 57, central Hula Peat soil drained waters, during 1994-2006.

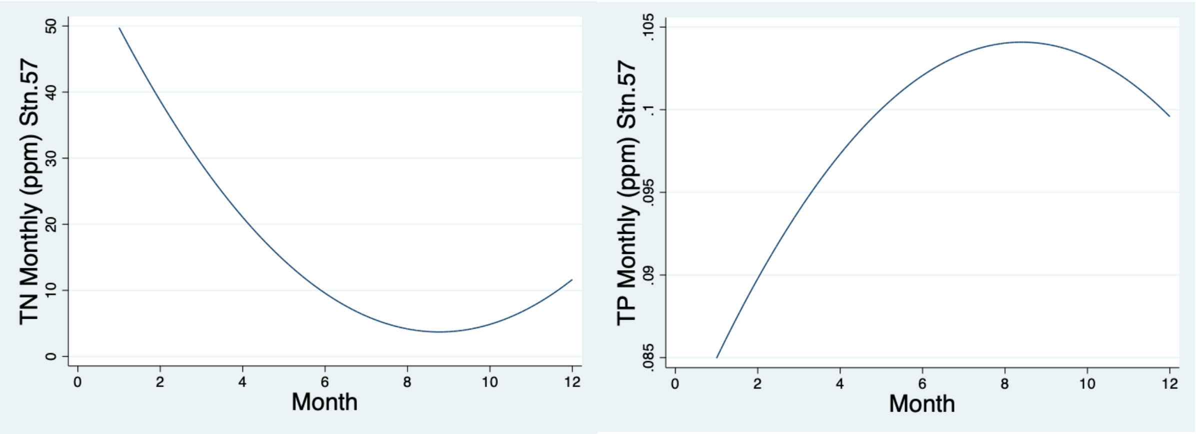

Figure 4. Quadratic regression plot of Seasonal (monthly) changes of TN (left panel) and TP (right panel) concentrations measured at Station 57, central Hula valley Peat soil block during 1994-2006.

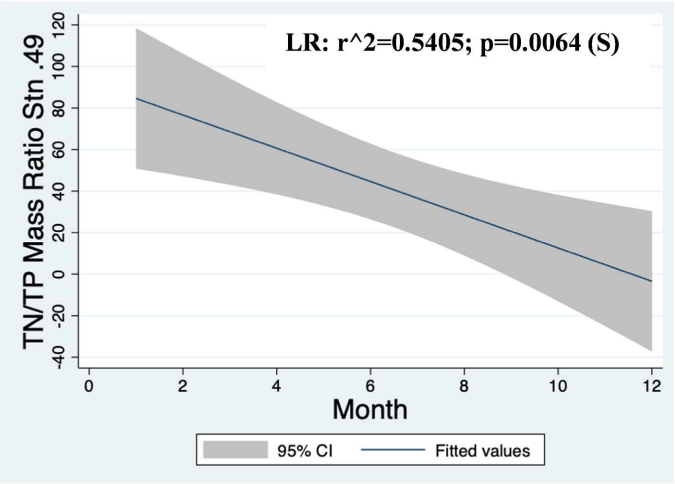

Figure 5. Monthly means of TN/TP mass ratio measured in Station 49, Lake Agmon-Hula (LAH) effluent exit, during 1994-2006.

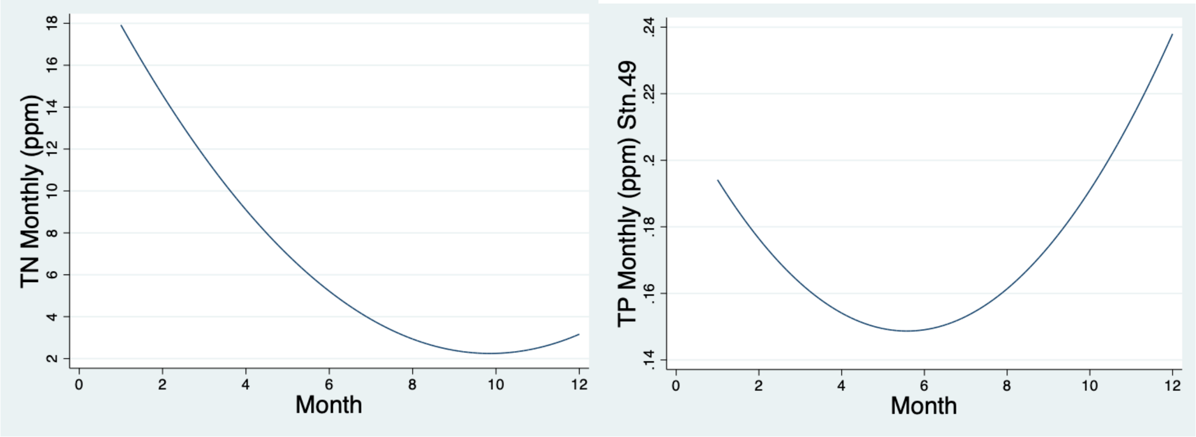

Figure 6. Quadratic regression plot of Seasonal (monthly) changes of TN (left panel) and TP (right panel) concentrations measured at Station 49, Lake Agmon-Hula (LAH) effluent exit during 1994-2006.

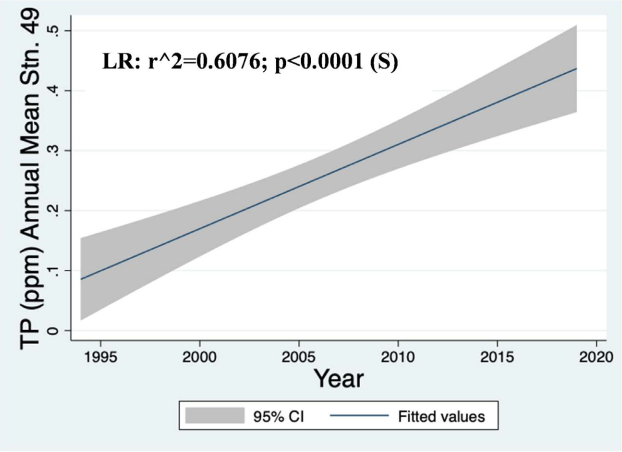

Figure 7. Linear Regression (prediction) plot of temporal (1994-2019) changes of annual mean TP concentration in the Lake Agmon-Hula effluent (Stn.49). Regression parameters are indicated (S = significant).

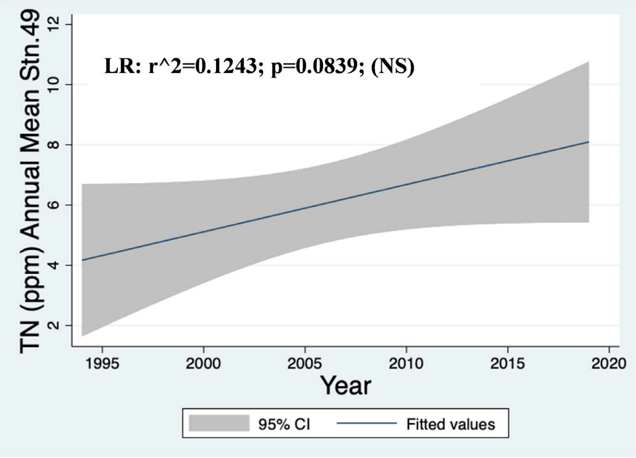

Figure 8. Linear Regression (prediction) plot of temporal (1994-2019) changes of annual mean TN concentration in the Lake Agmon-Hula effluent (Stn.49). Regression parameters are indicated (NS = Not significant).

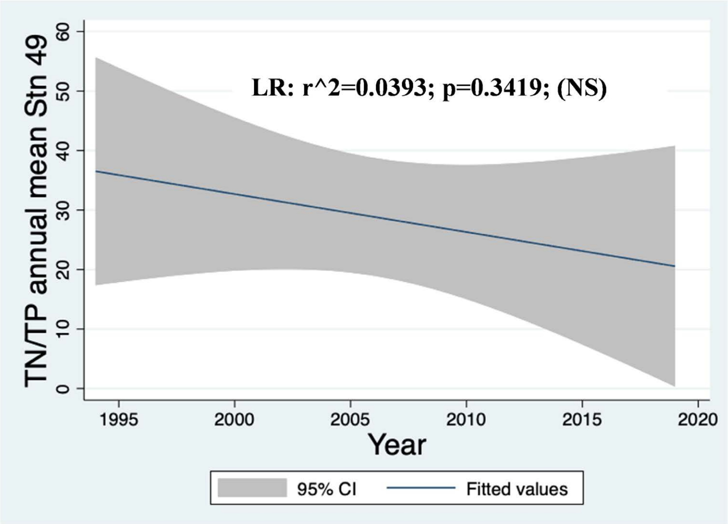

Figure 9. Linear Regression (prediction) plot of temporal (1994-2019) changes of annual mean TN/TP mass ratio in the Lake Agmon-Hula effluent (Stn.49). Regression parameters are indicated (NS = Not Significant).

4. Discussion

The documented number of vascular plant species was 53 and 147 (35 invaders included) during pre- and post-wetland drainage, respectively [12]-[23]. The Hula wetlands drainage and later the Hula Reclamation Project (HP) implementation created an increase in the variability of ecological habitats, including terrestrial, aquatic, and semi-aquatic internal components. Ecological diversity of Enrichment enhanced species biodiversity of submerged, emerged, and floating aquatic plants as well as terrestrial Species.

During the early 1990s, an unexpected, unique development, which had never been documented before, was observed in the Hula Valley, the migratory Crane case. As of the early 1990s, Cranes were rarely observed in the Hula Valley, nor prior to either post-Wetlands drainage. Peanuts cultivation created available food resources for winter (October-March) stopover for $30 - 55 \times 10^3$ Cranes (*Grus grus*). Since the mid-1990's LAH has been efficiently utilized as Crane's night-roosted sheltered location where potential mammalian predators are avoiding aquatic hunting. An 8 - 9 hour stay of thousands of large-bodied satiated birds was suspected to be a rich Phosphorus source through their droppings, possibly confounding vegetation contribution. Surprisingly, TP and TN of LAH waters records have indicated the lowest concentrations during Crane seasonal stay (December -March), whilst a distinct enhancement is observed in summer-fall months when Cranes are absent [8].

Nitrogen (N) and Phosphorus (P) availabilities are commonly limiting factors of the growth rate of terrestrial and aquatic plants. Nevertheless, plant responses as expressed by the N/P ratio are different. Moreover, anthropogenic intervention caused modification of P limitation in aquatic plants [24]-[26] and distributional diversity and densities [25] [26]. Environmental changes in nutrient availabilities resulting in the N/P ratio shifted the limitation impact from N to P [27]. Plant regulation of nutrient uptakes induces changes in the N/P ratio, up to a certain limit, in plant tissues [28]. The N/P ratio in plants is primarily regulated through P and N uptake mechanisms, and both the uptake dynamics and the fluid transported in the xylem are dependent on and sensitive to the phloem composition [29]. The N/P ratio regulation might be positive and negative as well. P-deficient plants increase the rate of P uptake and reduce the N consumption rate [30]. In other words, P uptake is enhanced in response to P deficiency [31].

Results given in **Table 2** emphasized the high demands for Nitrogen supply (high N/P ratio) by the aquatic floating algal vegetation and the much lower demands for Nitrogen, whereas high requirements for Phosphorus supply (low N/P ratio) of submerged and emerged vascular plants. Results given in **Figure 2** also indicate a temporal decline of the aquatic DW biomass in LAH, whilst the significance level is low. A similar trend was recorded for the TN and TP vegetation loads, whereas the opposite (temporal increase) was documented for the TN/TP mass ratio changes (**Figures 3-5**). Consequently, a decline in available Phosphorus stock in the LAH bottom sediments is suggested.

Results given in **Table 4** indicate the lowest and highest TP content in the southern and northern regions, respectively. Whilst TN content in central northern bottom sediments is the highest and lowest, respectively. Low Phosphorus and high Nitrogen content in the southern and central bottom sediments, respectively, are emphasized. Consequently, it is suggested that although the Phosphorus content in peat soil is high, it is unavailable under aquatic (wettability) conditions.

Results shown in **Figure 5** and **Figure 6** indicate the low value of the TN/TP mass ratio as an indication of a higher level of demanded P consumption. *C. demersum*, *P. paspalodes* and *T. domingensis* are probably more sensitive to insufficient available P in the bottom sediment substrate. Nevertheless, while aquatic conditions induce the availability decline of P in the coastal environment (*P. paspalodes*), where dryness is more frequent and availability of P is therefore enhanced [10].

Comparative scaling of Nitrogen and Phosphorus migration from LAH and their input loads into Lake Kinneret highlights the potential ecosystem relation: Total inputs of Phosphorus and Nitrogen into LAH, as averaged for 2008-2018 [32], are 0.9 and 86 tons, respectively. The total outflows of phosphorus and nitrogen from LAH are 2.14 tons and 58 tons, respectively. Consequently, additional Phosphorus contributions by aquatic plants are 1.24 tons *i.e.*, 1.6% of the total supply through the Jordan River. The annual average (2008-2018) LAH Nitrogen effluent is 58 tons, that is, the LAH ecosystem is a sink function for Nitrogen by 28 tons.

Based on the evaluated Linear Prediction (Regression) of temporal changes of TP concentration, a mean periodical (1994-2004) decline of 30 ppb in Station 57, averaged increase of 60 ppb in Station 49 (LAH effluents). Moreover, an average 30 ppb increase of TP concentration in Station 57, whilst a mean 360 ppb increase in Station 49 (LAH effluent) during 1994-2019 was documented. Consequently, a distinct TP extension to the LAH waters is due to aquatic plants. Results given in **Figure 2** and **Figure 3** indicate a seasonal decline of the TN/TP mass ratio resulting from either TN decline or TP enhancement or both. Results given in **Figures 4-6** indicate a seasonal decline of the TN/TP mass ratio resulting from either TN decline or TP enhancement or both. It should be taken into account that the TP concentration of TP as measured in drained water mediated Phosphorus represents both bioavailable and particulate components. Moreover, **Figures 2-6** emphasize overwhelmed nitrogen (TN) and phosphorus (TP) deficiency sources as reflected by the decline of the TN/TP mass ratio, which characterizes the Hula Valley ecosystem. An outcome of the optional implication of spatial distribution restriction of high phosphorus-demanding consumers, such as *Ceratophyllum demersum*, *Typha domingensis*, and *Paspalum paspalodes*, is suggested. The long-term (1994-2019) record of TN, TP and TN/TP mass ratio (**Figures 7-9**) confirms a significant increase in TP in LAH (Stn.49) whilst the TN increase and TN/TP decline are insignificant. It is therefore confirmed that the Nitrogen source in the Hula peat soil is of luxury status, whilst Phosphorus in the peat soil is deficient.

The nutrient composition in the bottom sediments' substrate of LAH indicates overwhelming nitrogen and a limited status of Phosphorus. The consequence rate of their uptake by the aquatic vegetation is reflected. Such a related interaction justifies the consideration of Liebig's law by respective interpretation: the factor at a minimal level among others is preferably consumed, which in our case, is due to Phosphorus preference. Nevertheless, the P preferred rooted uptake is transferred towards the bottom layer of plant tissues, creating an accumulated stock there during the seasonal, spring-early summer, biomass onset development. During the late summer-fall season of biomass offset degradation, the P stock is transported into the water of the wetlands. Consequently, the higher the uptake of "Liebig's" sedimented P minimal factor, the higher the TP migration to the LAH waters, which are measured as effluents (Station 49). The submerged and emerged LAH plant growth is dictated by the scarcest (the limiting factor) and not by the total available resources. Liebig's law was widely applied to ecosystem models for nutrient availability factors.

Three eco-geochemical factors and the Crane migration are correlated with phosphorus cycling in the Hula Valley: 1) The Peat-soil properties; 2) The Seasonal impact of climate conditions, *i.e.*, the impact of soil wettability (Rain and irrigation)-dryness alternate; 3) Night roosting of the migrated Cranes and potential phosphorus enrichment through birds dropping, that was suspected being a significant factor. The scope of this paper is Phosphorus cycling in the LAH ecosystem. The environmental complexity of the LAH ecosystem, and the correlative interaction between Phosphorus cycling and other ecological factors are considerably focused. The contribution of night roosting Cranes during fall-winter months was found to be insignificant. The contradiction between Nitrogen and

Phosphorus seasonal migration capacities from the Peat soil indicates a high TN level in winter-spring and lower during summer-fall and the opposite is true for TP (**Figure 4**). In other words, an increase in Peat soil moisture results in a reduction of TP migration. The Peat soil irrigation in summer therefore reduces TP migration which occurs naturaly in winter [33]. The seasonal fluctuations of Phosphorus and Nitrogen migration from peat soil consequently affect seasonal changes in TN/TP mass ratio in LAH water and in submerged and emerging vegetation biomass.

The Phosphorus uptake by rooted submerged and emerged plants was dictated by Liebig's law of minimal element consumption. Therefore Phosphorus was consumed and consequently stored in plat tissues more intensively than Nitrogen expressed as TN/TP mass ratios varies. On the other hand, plant tissue degradation enhanced Phosphorus concentration in the waters of LAH. The P transfer from the sediments into plant tissue and the P transfer from the plant tissues into the water are two dissimilar developments. Phosphorus enrichment of the LAH waters is slightly sourced continuously directly from the sediments through geochemical processes, microbial activity and advected upward micro porewater flows [3] [4]. Phosphorus transfer through vegetation biomass degradation occurs in the late summer-fall season. It should be considered that plant tissue degradation is a complicated geochemical process comprised of different chemotype affinities. The LAH sediments contain high loads of Gypsum and organic matter which create optimal background for the production of toxic sulfide of which non-toxic concentration was scarcely documented (6 - 8 μM) [3]-[5] [34]. Fertilized management in the wetlands of Everglades [35] [36] by Phosphorus and Nitrogen was indicated as an efficient factor which enhanced biomass production of *Cladium jamaicense* and *Typha domingensis,* confirming the shortage in those nutrients. The close relation between the global distribution of *Typha domingensis* and Phosphorus availability, that was documented [37], emphasizes its role in wetlands ecosystems. The Phosphorus cycling processes include the creation of several Phosphorus fractions such as, Soluble Reactive P (SRP), particulate P, organic and inorganic P, Total Dissolved P etc. Each one of these P-form has its own chemical dynamics which excludes the scope of the present study. A significant correlation obviously exists between submerged and emerged vegetation and biomass content of TP and TN (**Figure 2**; **Table 2**). Temporal information about TP, TN and TP/TN mass ratio (**Figure 2**; **Table 2**) indicate enhancement during the early 2000's with the exception of 2003. Rain capacity during 2003 was exceptionally high followed by high LAH's surface water level. Water level elevation in LAH induces a reduction in light intensity penetration towards sediment surface, *i.e.* attenuation enhancement, and consequently reduces seeds germination capacity and consequently onset development of young plant growth rate.

Results given here indicate temporal enhancement of TP concentration in the record of Station 49, LAH effluents. It looks like a paradox, "Liebig's" minimum P element rooted uptake, enhanced LAH's water TP concentration. A disputed paradoxical or contradicted situation is created: insufficient P in the bottom sediments is ended by LAH's water P concentration enhancement. Its probable settling comes through the LAH ecosystem structure and aquatic vegetation seasonal dynamics: minimal rooted P element uptake accumulation during submerged biomass onset, which is later transported as dissolved TP through the biomass offset process. A complexity resolved premise model suggested in this paper includes limiting factors of rooted P uptake followed by agglomeration within plant tissues, ending later by water P enrichment. This optional model might be relevant to shallow lakes, wetlands, and/or constructed wetlands.

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Author Contributions

The author carried out data analysis, evaluation and the preparation of the original MS document.

Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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