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Secretion of Phosphorus by Aquatic Plants Has an Impact on Their Phosphorus Uptake Budget. The Concept of Phosphorus Recycling

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According to the Directive 2000/60/EC of the European Parliament and of the Council (short EU Water Framework Directive; Union, 2000) phosphorus is one of the main water pollutants. But it is also one of the main plant nutrients, essential for diverse biochemical processes. Thus, in vegetated bodies of water, aquatic plants play an important role in nutrient turnover processes (Reddy, 1983; Reddy and De Busk, 1985; Bowden et al., 2007; Angelstein and Schubert, 2008; Volkmann et al., 2016) and become increasingly recognized within water quality management strategies (Union, 2000; Vermaat and Gross, 2016).

However, different authors described a significant release of phosphorus by diverse aquatic vascular plant species (for instance McRoy and Barsdate, 1970; DeMarte and Hartman, 1974; Twilley et al., 1977; Angelstein and Schubert, 2008). This secreted phosphorus is partially bioavailable and become thus again part of aquatic turnover processes, including via absorption by epiphytic biofilms or macrophytes itself. Thereby, a substantial release of phosphorus might first take place above a specific threshold of the phosphorus content in the plant tissue, as it was exemplarily shown for *Elodea nuttallii* (Angelstein and Schubert, 2008; Angelstein, 2009) (**Figure 1**). The achievement of this threshold level seems to depend on the specific phosphorus-uptake kinetic and the phosphorus content in the plant-tissue. Since the phosphorus concentration in the tissue itself mainly depends on the bioavailable phosphorus of the surrounding media (water or sediment) (Angelstein and Schubert, 2008; Baldy et al., 2015), it becomes clear, that the importance of released phosphorus as a possible phosphorus source (recycling) increase with increasing nutrient concentrations, and thus under meso- and eutrophic conditions.

This concept of phosphorus recycling (**Figure 1**) highlights the importance to distinguish between net- and gross-uptake, especially in such cases where a theoretical nutrient uptake by macrophytes, or aquatic plants in general should be estimated for aquatic ecosystems like lakes, reservoirs, wetlands, estuaries, ocean bays and waste waters treatment plants. However, in the moment only net-uptake processes can be estimated, since it is actually impossible to distinguish between different phosphorus sources. The development of new, non-hazardous techniques or experimental approaches is a challenge for the future.

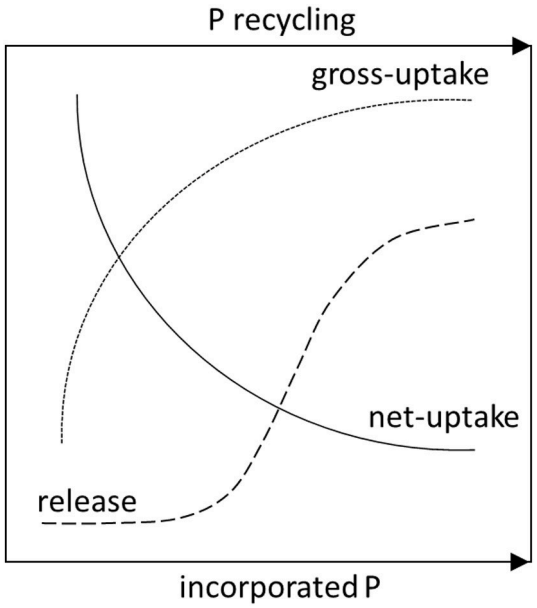

FIGURE 1 | The concept of phosphorus recycling based on the balance-scheme of phosphorus uptake by *Elodea nuttallii* (adapted from Angelstein, 2009): The measureable net-uptake and release (secretion) of phosphorus by *E. nuttallii* plants seems to depend on the phosphorus content in the plant tissue and the recycling of already released phosphorus. Thereby, a substantial phosphorus release (broken line) might first take place above a specific threshold of the incorporated phosphorus. The net-uptake rate (black line) of phosphorus decrease or become stable with increasing recycling and thus with an increase of phosphorus incorporated in the plant tissue. In parallel the gross-uptake rate (dotted line) might increase up to a specific level of incorporated phosphorus. The presented concept is a simplified scheme, and thus contains neither units, nor any data.

In conclusion, phosphorus recycling processes exist, and—as it was exemplarily shown for *E. nuttallii*—might become significant with an increasing phosphorus content in the plant-tissue. Phosphorus recycling is a complex mechanism, difficult to analyse. The extent of phosphorus release as well as the kinetic of phosphorus uptake (including recycling) itself is affected by divers environmental and plant internal parameters. However, the existence of mechanisms like recycling processes highlight that we need to rethink our understanding on nutrient uptake rates in general, since they are not as clear as commonly assumed. The detection of the gross-uptake rate is a challenge for the future, since the distinction between gross- und net-uptake rates is important, especially in the glance of future water management strategies.

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This manuscript was written by SH and is based on parts of her own work. SH had also the idea to this opinion article.

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