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REVIEW ARTICLE

Environmental perspectives of *Phragmites australis* (Cav.) Trin. Ex. Steudel

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Abstract Extensive research is being conducted worldwide to find alternative and efficient systems to lessen the impacts of climate change and reduce environmental pollution. The genus *Phragmites* has proven ability to mitigate the environmental pollution of its surroundings. Common reed (*Phragmites australis* (Cav.) Trin. Ex. Steudel), a graminaceous plant of cosmopolitan nature, has been extensively studied especially for the mitigation of environmental contamination. The capability of common reed to grow well at extreme environmental conditions such as elevated CO_2 and high temperature is conferred by several factors such as change of carbon trapping mechanism (from C_3 to C_4 and vice versa), microbial association and biochemical adaptations. *P. australis* has been a most preferred unique plant system, especially in ecological engineering for improving the quality of wastewater. This paper reviews the current state of knowledge regarding the suitability of *Phragmites australis* for environmental remediation and summarizes recent advancements in our understanding of this grass.

Keywords *Phragmites australis* · Environmental contamination · C_3 · C_4 · Ecological engineering

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Introduction

The genus *Phragmites* of family Poaceae comprises of the most common perennial, rhizomatous, stoloniferous and tall (2.0–6.0 m) grasses, viz., *Phragmites australis*, *P. karka*, *P. communis*, *P. longivalvis*, *P. maxima* and *P. prostrata* (Poonawala et al. 1999), of temperate and tropical wetlands all over the world. *P. australis* (common reed) and *P. karka* (flute grass) are two commonly occurring members on the Indian sub-continent. The geographical distribution of *Phragmites* spp. extends from cold temperate regions to the wetlands of hot and moist tropics (Lessmann et al. 2001), although the transitional zones (ecotones) of rivers, big lakes and wetlands are the most preferred habitats of the common reed (Kenneth and Biddlestone 1995). *P. australis* seeds profusely and spreads vegetatively by a vigorous system of rhizomes and stolons (Hara et al. 1993; Marks et al. 1994) rendering it cosmopolitan in nature. Figure 1 show the global distribution of the genus *Phragmites*. The competitive nature of *P. australis* reflects the plant's adaptive features. Studies show that *P. australis* grows in soils of different pH, salinity, fertility and textures, and attains high productivity under different climatic conditions (Dinka and Szeglet 1998). Voluminous literature is available on the ecological significance of *Phragmites* (Marks et al. 1994; Coops et al. 1996; Brix 1999; Clevering and Lissner 1999; Meyerson et al. 2000; Clevering et al. 2001; Ostendorp et al. 2003; Häfliger et al. 2006; Nechwatal et al.

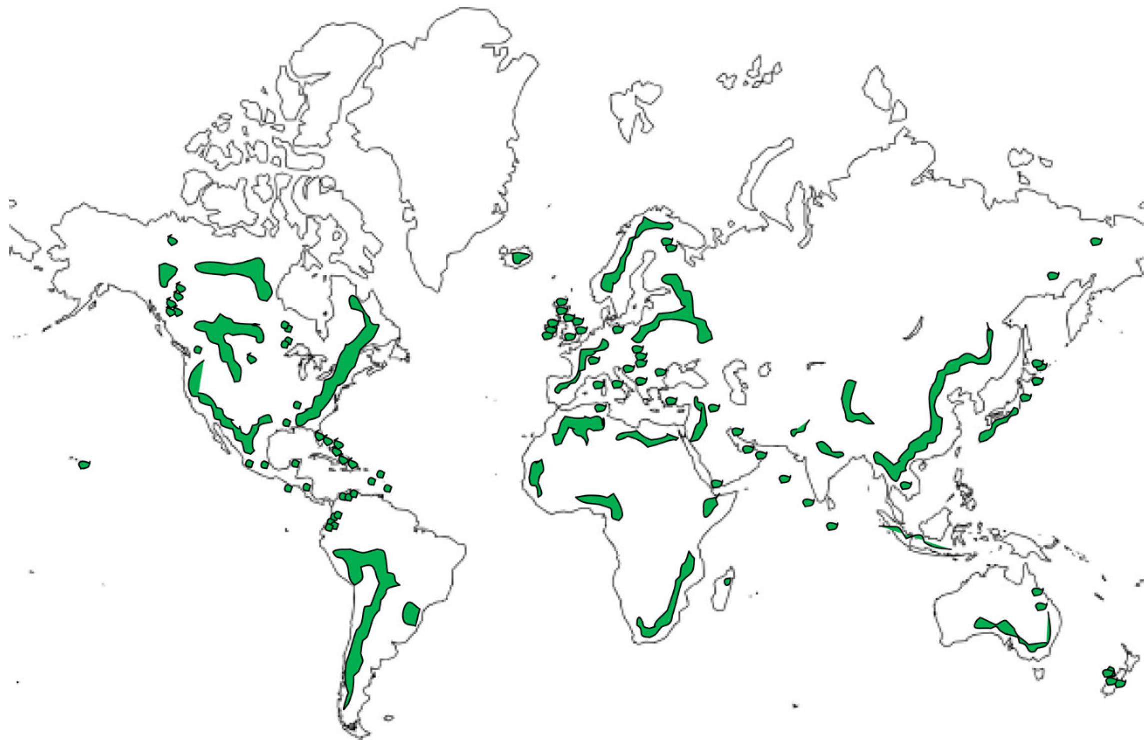

Fig. 1 World map showing the distribution of *Phragmites australis* over the continents. *Green strips* show the global infestation of *Phragmites australis*. The infestation map shows only those identified regions on the earth where the species *P. australis* has been reported; however, species other than *P. australis* may also be present

2008; Weidenhamer et al. 2013). The use of *Phragmites* species in India is conventional, primarily as raw material for rayon and paper pulp (Poonawala et al. 1999). Species of genera *Phragmites*, chiefly *australis*, *karka* and *communis*, are well documented for their ability to mitigate environmental pollution (Singh and Srivastava 2007; Srivastava 2008; Srinivasan et al. 2000). *Phragmites australis* has been the most preferred plant among the ecological engineers for its application in constructed wetlands (Kadlec and Knight 1996; Brix et al. 2003; Garcia et al. 2004; Vymazal and Kröpfelova 2005; Wang et al. 2010). In this review paper, comprehensive ecological and environmental applications of *Phragmites australis* (common reeds) have been reviewed to understand the use of this grass in environmental protection engineering with a summary of recent advancements in our understanding.

Ecology of *Phragmites australis* (Cav.) Trin. Ex. Steudel

An adaptive amphibious species

Phragmites australis is a transitional species of two closely attached ecosystems, viz., aquatic and terrestrial, and commonly occurs in marshy wetlands (Mal and Narine 2004). The ecological significance of *P. australis* has been realized worldwide and it is a well-known environmentally resilient species. The growing period is long in most of the subtropical and mild temperate zones, facilitating reed plants to obtain all the essential adjustments to the variations in temperature, soil nutrients and available oxygen (wetlands) together with certain physiological features such as transpiration rates in connection to the seasonal variations (Haslam 1972). The rhizomes of *P. australis* are highly preserved as these remain buried in the soil and sediments, which help provide protection from frost and fire. The rhizomes do not survive in anaerobic conditions as a result of long flooding (Ostendorp et al. 2003), indicating shorter growth length in such conditions. The disappearance of rhizomes of *P. australis* under flooded conditions has also been observed and are found to be completely replaced by adventitious roots (Srivastava 2008). In anaerobic conditions as a result of inundation, the expression of anaerobic stress proteins (ANPs) enables oxygen-independent energy generation in the common reed plants through metabolic processes, a common feature of most of the plant systems growing in anoxic conditions (Subbaiah and Sachs 2003). High transpiration rate of *P. australis* growing under flood-like conditions display an adaptive feature, protecting it from waterlogging especially in summers and at mild temperate regions (Borin et al. 2011). Figure 2 shows the general biological attributes of *P. australis*.

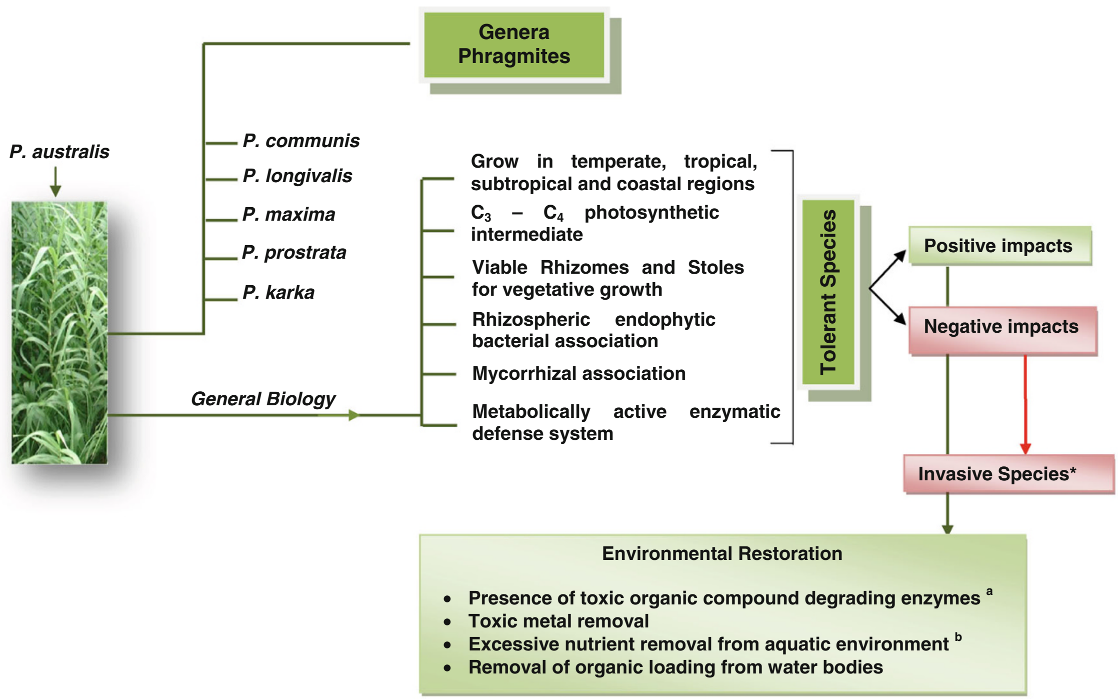

Fig. 2 General attributes of *Phragmites australis* (Cav.) Trin. Ex. Steudel. Six species of genus *Phragmites* have been reported so far (Poonawala et al. 1999); out of these six, *P. australis* is cosmopolitan. **a** (Chu et al. 2006); **b** (Brix et al. 2003). *Asterisk* invasions by *Phragmites* species have been reported in northeastern USA, Europe and Australia, but no report of such invasion is available from the rest of the world. However, the introduction of this grass from Europe to the world countries cannot be overlooked

Photosynthetic intermediate

P. australis is a C_3 plant; however on the basis of habitats, four C_3–C_4 photosynthetic intermediate ecotypes are known, viz., C_3, C_4 species that evolve in swamp; C_3–C_4 intermediate ecotype; C_3 species that evolve in dry land; and C_3–C_4 intermediate ecotype in saline environment have been reported by Zheng et al. (2000). Having both C_3 and C_4 type of photosynthesis in plants allows them to compete better to the changing environmental conditions (Srivastava et al. 2012). Switching to the C_4 photosynthetic mechanism renders to *P. australis* perfect protection necessary to survive in extreme environments. This may be one of the factors responsible for the global occurrence of *P. australis*. A detailed discussion of tolerance imparted through the photosynthetic intermediates has been included later in this review.

Microbial association

The root zone of *P. australis* is rich in dissolved oxygen as well as in organic carbon, providing optimal conditions required for microbial colonization. Mycorrhizal ecotypes of *P. australis* have also been reported (Oliveira et al. 2001), although mycorrhization (mostly by the members of the Glomeraceae family, e.g., *Glomus fasciculatum*, *Glomus mosseae*) is altered significantly depending on the soil moisture and temperature conditions. Mycorrhization generally helps establish plants in extremely disturbed sites (Oliveira et al. 2001). *P. australis* grows well on drying sedimentation ponds, polluted river banks, quarried fields and other disturbed sites (Roman et al. 1984) and at extreme saline conditions (Al-Garni 2006). The rhizosphere of *P. australis* contains a variety of aerobic microbes (Chaturvedi et al. 2006), e.g., *Microbacterium hydrocarbonoxidans*, *Achromobacter xylosoxidans* and a number of species belonging to the genera *Bacillus* and *Pseudomonas*. In general, most bacterial species of the rhizospheric microbial community act as plant growth promoters (PGP), especially in wetland plant species. Okabe et al. (2012) reported the presence of *Nitrosomonas*-like ammonia oxidizing bacteria (AOB), indicating that nitrification occurs under waterlogged conditions. Li et al. (2013) reported specific root zone-associated microbial community including Acidobacteria, Actinobacteria, Nitrospirae and Spirochaetes in *P. australis*.

Salt enrichment and *P. australis*

Germination of many wetland species is influenced by salinity, temperature and light at the surface (Ekstam et al. 1999). Seeds of *P. australis* germinate under a broad range

Table 1 Characteristics of C_3 and C_4 plants under altered climatic conditions, clearly defining the strategies of plants to survive under extreme environment

Response parameters	C_3 under elevated CO_2 and temperature	C_4- under elevated CO_2 and temperature	References
Photosynthetic activity	Cold conditions preferred	Higher temperature resistant	Weber and Caemmerer 2010; Ueno 2001
Photorespiration	Can exceed 30 %	Hardly achieve 5 %	Sage 2004
Light use efficiency	Lesser	Greater	Bräutigam and Hoffmann-Benning 2008; Evans 1993
Biomass (gm dry wt.)	Slightly < C_4 (33 %)	Slightly > C_3 (44 %)	Sage 2004; Wand et al. 1999
Mycorrhization	Lesser	Higher	Tang et al. 2009; Treseder 2004
Water use efficiency	Less efficient	Highly efficient	Derner et al. 2003; Winslow et al. 2003
Nitrogen use efficiency	Less efficient	Highly efficient	Niu et al. 2006; Edwards et al. 2005
Stomatal conductance	High	Lower	Caird et al. 2007

From (Srivastava et al. 2012)

of conditions (Greenwood and MacFarlane 2006). Reeds are facultative halophytes (Saltonstall 2002) that grow well in high salinity up to 30 ‰ (Asaeda et al. 2003) and accumulate amino acids and sugars to maintain the osmotic potential and cell turgor (Hartzendorf and Rolletschek 2001). High K^+ concentration in leaf tissue, an important factor for salt tolerance (Lissner et al. 1999), is mediated by K^+ transporters resulting in high K^+/Na^+ ratio (Takahashi et al. 2007). This is largely influenced by Ca^+ ions in *P. australis*, whereby calcium ion accumulation increases the K^+/Na^+ ratio, thus imparting tolerance to the plant for salt stress depending on the increased water potential and stomatal conductance (Pagter et al. 2009; Gorai et al. 2010). In conclusion, *P. australis* is a well-equipped plant with physiological characteristics to manage its own sustenance in stressful environments.

Understanding the tolerance of *P. australis*

P. australis has a unique adaptive feature to withstand hostile environment. Unique photosynthesis ability of *Phragmites* (as mentioned in "Photosynthetic intermediate" section), attributable to its C_3–C_4 intermediate characteristic (although *P. australis* preferably follows C_3 pathway) and because of mono-specific stands (as a result of vegetative reproduction) out-compete native vegetation (Kettenring et al. 2010). Table 1 shows some of the characters of C_3 and C_4 plants growing in altered climatic conditions. Switching over from C_3 to C_4 mechanism helps trap atmospheric carbon dioxide (CO_2) most efficiently, supporting carbohydrate allocation to the rhizomes. Stored carbohydrates in the rhizomes ensure the survival of plant and maintenance of root-associated endophytic bacterial community (Li et al. 2010) and mycorrhiza during extreme environmental conditions. In addition, oxygen transport from above to belowground plant parts via aerenchymatous tissues ensures the survival of aerobic microbial

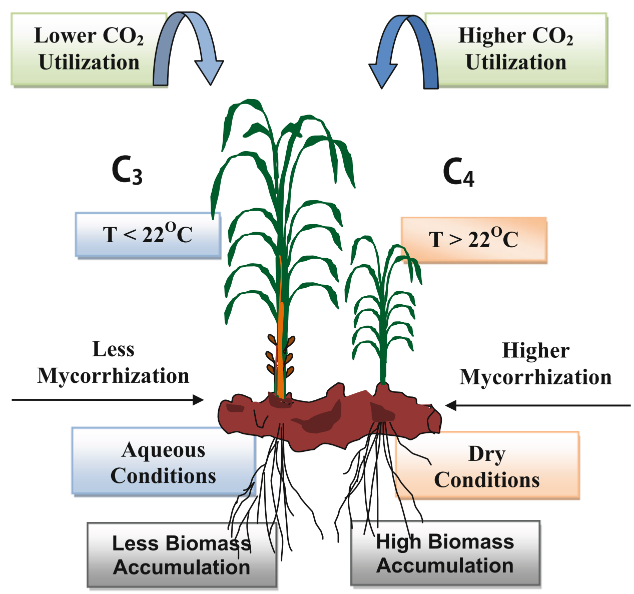

Fig. 3 The C_3–C_4 ecotype of *P. australis* and its survival strategies

communities associated with the roots. *P. australis* maintains carbon content in the rhizosphere as a result of root exudates containing phenols, short-chained organic acids, sugars and amino acids. This is the sole source of carbon to the *Mycobacterium* spp. capable of degrading toxic organic compounds such as benzo[a]pyrene (Toyama et al. 2011a). Toyama et al. (2011b) reported that bacterial species, viz., one strain of *Stenotrophomonas* sp. and two strains of *Sphingobium* spp. isolated from the rhizosphere, were found to have reducing ability for toxic organic compounds such as 4-*tert*-octylphenol. Figure 3 shows the survival strategy of *P. australis* in two types of environmental conditions, viz. moist and cold and warm and dry. However, for optimal growth, common reed being a hydrophyte needs plenty of water availability (Winslow et al. 2003). At higher atmospheric temperature, senescence caused the death of C_3 plants because of reduced CO_2 fixation and increased respiration; however, C_3–C_4 intermediate ecotypes of *P. australis* can tolerate such conditions. Mycorrhizal association in *P. australis* also helps tolerate high salinity as it prevents water loss significantly (Al-Garni 2006). Many wetland species exhibiting radial oxygen loss show the unique feature of iron plaque being deposited on mature parts of their roots (St–Cyr and Crowder 1988) reducing the chances of toxic metal absorption through diffusion (Greipsson 1994). *P. australis* is a wetland species and has been reported to have iron plaque of Fe III on its root surface (only when growing in an iron-rich condition) and a lignified, suberized rhizodermal cell layer protecting roots from noxious substances causing reduced oxygen level at root zone (Batty et al. 2000). It also protects root tissues from the toxic effects of intruding metals such as Cu, although to a lesser extent (Ali et al. 2002). Moreover, faster growth and higher biomass accumulation help *P. australis* tolerate the toxic effects of metals and other toxicants (Bragato et al. 2006). Evapotranspiration (ET) rates are high in *P. australis* which also helps protect plants under inundation (Borin et al. 2011) during flood-like conditions (Ostendorp et al. 2001); however, strong flooding can cause damage by separating leaves from the air supply. If a sufficient part of the leaves remain in contact with the air, the reeds survive. Reed plants are also able to survive in low pH conditions (Haslam 1972; Nixdorf et al. 2001) as the roots and rhizomes are largely protected by hypodermal thickening of lignin and wax on the surface, preventing the penetration of undissociated organic acids at low pH, which are lethal because such chemicals pass through biological non-polar membranes. Moreover, the root exudates contain HCO_3^{1-} ions that provide buffering to the *milieu interior*. ET is also associated with the tolerance of this plant against toxic metals by releasing water-containing metal ions through the leaves (Windham et al. 2001).

Environmental restoration by *P. australis*

Removal of nutrients and organic compounds from polluted water

The influx of nutrient ions such as phosphate, nitrate, potassium and calcium from the non-point sources, especially through lateral diffusion, is significant on the shores of natural water systems causing enrichment of water and impairment of water quality (Knight et al. 2000; Srivastava et al. 2011). Approximately, 60 % of the input of inorganic nitrogen into the water is estimated to be due to human activities such as human settlements (sewage) and agriculture (Nimptsch and Pflugmacher 2007). *P. australis* has an important role in mitigating this water pollution. It has been the most preferred research plant for pollution mitigation from wastewaters, especially in engineered wetlands. *P. australis* accumulates almost twice as high concentration of phosphorus (PO_4^{3-}) and potassium in the below and aboveground plant parts as compared to other emergent macrophytes, which help to remove excessive nutrient ions from environmental matrices (Singh and Srivastava 2007). *P. australis* maintains constant oxygenation of the rhizosphere resulting in the oxidation of ammonia (NH_3) to nitrate (NO_3^-) (Brix et al. 2003). *P. australis* is also capable of degrading organo-chlorine compounds such as DDT and polychlorinated biphenyls (PCBs), which is partially mediated by enzymes like peroxidase and plant P-450 system (Chu et al. 2006). Voluminous literature (Brix and Schierup 1990; Cooper 1999; Greenway and Wooley 1999; da-Motta-Marques et al. 2001; Peltier et al. 2003; Brix et al. 2003; Solano et al. 2004; Toet et al. 2005; Bragato et al. 2006; Mant et al. 2006; Lee and Scholz 2007, Bianchi et al. 2011) and the references therein are available on various aspects of pollution and excessive nutrient removal through *P. australis.* For the treatment of industrial wastewater (Cooper et al. 1996) and urban wastewater (Srinivasan et al. 2000), *Phragmites* spp. have been widely used in constructed wetlands (Scholz and Xu 2002; Scholz 2003; Stottmeister et al. 2003; Kaseva 2004; Solano et al. 2004; Srivastava et al. 2008) for the treatment of the most common parameter, 5 day BOD; however, the findings show a negative correlation with *P. australis* which is the only cost-effective stand-alone treatment of raw wastewater.

Removal of heavy metals

Removal of toxic heavy metals from the aquatic environment is one of the priorities of the environmentalist all over the world. *P. australis* is one of the most studied aquatic plants for heavy metal removal (Schierup and Larsen 1981; Szymanowska et al. 1999; Ye et al. 2003; Samecka-Cymerman and Kempers 2001; Peltier et al. 2003; Windham et al. 2001; Ali et al. 2002; Mant et al. 2006; Chiu et al. 2006; Drzewiecka et al. 2010) because of its high metal removal potential (Table 2) and fast growth, accumulating metal in above and belowground biomass. In general, plants have a tendency to release excessive metal ions through transpiration, reducing the toxic concentration in the plant tissues of leaves which is common to *P. australis* also (Berk and Colwell 1981; Burke et al. 2000). Since, out of 53 heavy metals, only 17 are bio-available (Carranza-Alvarez et al. 2008), increased transpiration rates increase the bioavailability of metals in *P. australis*. Valuable findings of Southichak

Table 2 Environmental tolerance of *Phragmites australis*

Sr No	Physicochemical environment	Tolerance		References
		Range	EOT	
1.	Temperature	0–40 °C	+++	Haslam 1972
2.	Frost	–	+++	Weisner and Strand 1996
3.	Drought	–	− − −	Takahashi et al. 2007
4.	Flood	–	− − +	Ostendorp et al. 2003
5.	pH	2.9–8.1	+++	Haslam 1972
	Metals			
6.	Cd		+++	Wang et al. 2009
7.	Cu		− − +	Ye et al. 2003
8.	Zn		+++	Peltier et al. 2003
9.	Cr		− − +	Mant et al. 2006
10.	Mn		+++	Samecka-Cymerman and Kempers 2001
11.	Ni		− − +	Samecka-Cymerman and Kempers 2001
12.	Pb		++ −	Drzewiecka et al. 2010
	Metalloids			
13.	As		+++	Ghassemzadeh et al. 2008
14.	Sb		− ++	Ghassemzadeh et al. 2008

EOT + extent of tolerance, − − − not tolerant

et al. (2006) suggest wide tolerance in the reed against most of the toxic metals such as Cu, Ni, Cd, Zn and Pb. However, metal removal and accumulation depend largely on the growing period of plants and their physiological attributes (Windham et al. 2001). *P. australis* can withstand higher concentration >8.0 µM of Cu (Ali et al. 2002); therefore, it is also considered as a Cu-tolerant plant. Higher accumulation of Zn and Mn has been reported in the roots of *P. australis* (Peltier et al. 2003). The studies show the higher removal of metal ions by *P. australis* as compared to the other plant *Rhananculus spherosphermus* (Aksoy et al. 2005) and by *Spartina alterniflora* a marsh plant of North America (Weis and Weis 2004) with a decreasing trend of accumulation as roots > rhizome > leaf > stem (Bonanno 2011). As mentioned in "Microbial association", endophytic bacterial community comprising Gram-negative and Gram-positive bacterial species present in the tissues and on the surface of reed grass tend to enhance the uptake of metal ions from the environmental matrices, especially water (Li et al. 2010), which also confirm the findings of Keller et al. (1998) according to which most of the metals taken up by the common reed plant remain in rhizomes and roots. Removal of metalloids such as arsenic (As) and antimony (Sb) by the common reed plant has also been reported by Ghassemzadeh et al. (2008). A recent study of Ayeni et al. (2012) showed the abundance of metals in various parts of *P. australis* in the following order: Al > Pb > Cd > Co > Ni > Cr and for micronutrients Fe > Mn > Zn > Cu depending on the concentration in the environment.

Environmental demerits of *P. australis*

Methane emission

Phragmites dominate wetlands and provide a significant source of methane emission to the atmosphere (Brix 1999). High CH_4 emission rates characterize various wetlands occupied by *Phragmites* communities with average emission as high as 123 $gCH_4m^{-2}a^{-1}$ reported from meso-eutrophic lakes (Kankaala et al. 2004). The emission of CH_4 (methane) from wetland soil is a result of two contrasting microbiological processes, viz., anaerobic CH_4 production and aerobic CH_4 oxidation (Duan et al. 2009); however, oxygen availability and potential for aerobic degradation of organic matter and CH_4 oxidation increase when the water table is lowered. The studies indicate the contribution of *P. australis* plant in the emission of global warming-causing gas; however, interestingly *P. australis* being a C_3–C_4 intermediate has unique carbon dioxide trapping mechanism reducing the major culprit gas (CO_2).

P. australis an invasive species

Long historical research records prove *P. australis* to be an invasive species (Mal and Narine 2004; Rudrappa et al. 2007) that invaded from Europe to various parts of the world, especially the eastern part of North America (Saltonstall 2002) and southern Australia. There has been no report of invasion by *P. australis* to Asian countries. Wang et al. (2006) reported the reinvasion by *P. australis* into experimental marshes which was later blocked by regenerated native species, especially by *Spartina patens*; however, *P. australis* has reportedly been suggested to be more successful in replacing another species *Spartina alterniflora* of the same genera in the lower marshes of eastern USA (Weis and Weis 2004). *P. australis* invades chiefly via rhizomes and stolons. Rudrappa et al. (2007) reported the presence of gallic acid (3,4,5–trihydroxy benzoic acid), a chemical secreted by the roots of common reeds, caused the cell death of other plants (native species) conferring an invasive nature to *P. australis*, although recently Weidenhamer et al. (2013) reported no such correlation between invasiveness of common reed and gallic acid. As per Weidenhamer et al. (2013), the half-life of gallic acid is less than 1 day, which may not render any negative effect on other plants. The reports of Weidenhamer et al. (2013) indicate no role of gallic acid in imparting the invasive character of this grass as described earlier by Rudrappa et al. (2007).

Future studies

There are several potential opportunities still open as far as *P. australis* is concerned; for example, eco-physiological evidences for ascertaining the invasive nature of *P. australis* and mechanisms for the invasive character of common reed are still to be confirmed. The performance of *P. australis* in shoreline management at wetlands and in ecological turnover along with several other field studies are required to confirm the pollution mitigation ability of *P. australis* from the environmental matrices, especially under altered climatic conditions. Despite many research reports on the successful use of common reed in constructed wetlands for the treatment of industrial effluent of various nature, pilot-scale studies are still required to ascertain the use of this grass, especially in engineered wetlands in combination with microbial consortia for the treatment of municipal wastewater containing disinfectants and toxic heavy metals, water containing organic pesticides and in situ treatment of natural waters for, e.g., river water with the help of floating pontoons. Biomass-related studies are also an open field of research as *P. australis* accumulates metal ions in the tissues, which on removal of the entire biomass raise a serious concern of its management.

Conclusion

In conclusion, *P. australis* is the most successful perennial grass species having a well-established regime with no specific boundaries (Fig. 1). The grass has adapted to most of the extreme environmental conditions, for e.g., extreme cold or extreme warmth as well as dryness or wetness. Despite having a few environmental demerits such as invasiveness (which is still to be understood), scientists have proved its ability to restore the quality of environmental matrices. *P. australis* is used as a good source of roughage for cattle and the fibers for making paper (Mal and Narine 2004). Apart from these economic uses, *P. australis* is environmentally very sound. Research reports suggest the proven ability of *P. australis* to remove heavy metals cations, such as Ni, Cd, Cu and Pb, and other nutrient anions, such as PO_4^{3-} and SO_4^{2-}, from the aquatic environment. *Phragmites* spp. has enzymatic systems to degrade the xenobiotic organic compounds such as chlorinated pesticides and PCBs. It also helps maintain the oxygen level in water with the help of root-associated microbes.

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