

An overview of the patterned fens of Great Sandy Region, far eastern Australia

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SUMMARY

As far as is currently known, patterned fens of the Great Sandy Region (GSR; Australia) are globally unique in that they arise from the particular hydrological characteristics of a sub-tropical coastal dune system. This article outlines their extent, distribution, characteristics, values and threats. Seven distinct clusters of fens, containing 700 ha of obvious ‘patterning’ resembling that in temperate mires, cover a total area of around 7,000 ha within largely acidic (pH < 5) wet heath ecosystems. Unlike patterned mires in the Northern Hemisphere dominated by *Sphagnum* (moss) species, these examples are dominated by the restiad species *Empodisma minus*. Habitat is provided for many endangered fauna including frogs and fish adapted to the unusually acidic conditions. All of the GSR fens fall within the proposed Great Sandy World Heritage Area. The carbon sequestration process that characterises peaty environments makes these fens a fertile source of information on many aspects of environmental history. They are intrinsically sensitive to fluctuations in rainfall, evaporation and sea level, and thus to climate change. A more direct key threat is extraction of resources including, notably, groundwater. However, the fens have remained largely free from human disturbance since the early Holocene and, with their identification and recognition, the challenge now is to maintain these systems in their natural state and continue benefiting from the ecosystem services provided as a result of their excellent condition.

KEY WORDS: abstraction, coastal dunes, groundwater, RAMSAR, wet heath, World Heritage Area

INTRODUCTION

Peatlands (termed ‘mires’ when they are actively forming peat) are capable of sequestering atmospheric carbon for millennia (Yu *et al.* 2010, Charman *et al.* 2013). Known peatlands represent around one-third of the world’s wetlands and a third of known global soil carbon (Parish *et al.* 2008). The majority occur in boreal settings, many having been substantially altered by drainage for plantation forestry, flood mitigation and agriculture (e.g. Lindsay 1993, Holden *et al.* 2004); by fire, mining and permafrost melt (Turetsky *et al.* 2002); or by adjacent land use (Hoekman 2007), peat extraction and moss harvesting (Farrell & Doyle 2003). Peaty ecosystems are also sensitive to effects of climate change (e.g. Barber 1981, Gorham 1991, Barber *et al.* 1998, Belyea & Malmer 2004), notably alteration of hydrological regimes and increased evaporation leading to changes in vegetation, microtopography, patterning and carbon sequestration rates. Overviews of Southern Hemisphere peatlands (Gore 1983, Mark *et al.* 1995) and Australasian peatlands (Whinam *et al.* 2003) note the paucity of recorded examples and limited original areal extent, with the extra-tropical

Southern Hemisphere containing roughly 1M ha. Most examples occur in higher rainfall areas >34 °S.

Patterned mires (whether groundwater-fed ‘fens’ or precipitation-fed ‘bogs’) are so called when the mire surface obviously comprises repeated discrete patches of different vegetation types with or without pools of free water, typically at the tens of metres scale covering tens if not hundreds of hectares. The arrangement of patches and pools can form striking patterns when viewed from above. Illustrations of such patterning can be found in Gore (1983), Foster & King (1984), Foster *et al.* (1988), Steiner (2005) and later in this article.

Upon their ‘discovery’ in 1996, the patterned fens of the Great Sandy Region (hereafter ‘GSR’) gained global significance as the only known subtropical examples of patterned freshwater wetlands emanating from ancient sand-dune systems. Other patterned systems within similarly long-established sand-dune systems are known, but all of these lie within the northern boreal zone (e.g. Pakalne & Aleksāns 2017, Wołejko *et al.* 2019). The GSR region is already recognised at international level for its RAMSAR wetlands and World Heritage values (e.g. FIWHASAC 2004a, Twyford 1996). The fens

increase the significance of the Fraser Island World Heritage Area (FIWHASAC 2004b) and lend weight to the case for a proposed mainland extension (containing the Cooloola dune system) to form the Great Sandy Strait World Heritage Area (UNESCO/WHC 2018). While the World Heritage Area proposal mentions their presence in the region, patterned fens are specifically identified as knowledge gaps in relation to all of the aforementioned tenures (e.g. Twyford 1996, FIWHASAC 2004a, DERM 2011) which further include National Park, if not Marine Park, designations. Specifically, acknowledged information gaps embrace such questions as: What are these patterned systems and are they indeed patterned fens? What is their extent? What is their significance for biodiversity?

This article provides an overview of the patterned fens of the Great Sandy Region based on image analysis and GIS analysis, field observations (mainly in 2011) and literature review. It describes their extent, character, species of conservation significance, values and threats.

STUDY AREA

The study area is located on the south-east coast of the state of Queensland, Australia (Figure 1a) and is defined by the proposed Great Sandy World Heritage Area (Figure 1b) which comprises Fraser Island, the passage between this island and the mainland (the Great Sandy Strait), and the adjoining Cooloola coastal sand dunes (UNESCO/WHC 2018). The general area is known locally as the ‘Great Sandy Region’. The Great Sandy Strait is included in the description of the Great Sandy Ramsar Wetland (Wetlands International 1999). Key sub-international tenures are the Great Sandy National Park and the Great Sandy Marine Park (e.g. NPRSR 2018).

Fraser Island is the largest sand island in the world (Da Silva & Shulmeister 2016), containing approximately 200 km³ of sand (Boyd 2004). The Cooloola coastal sand dunes on the mainland are of comparable volume (60 × 17 km, up to 240 m a.s.l.) and have been described by Seymour (1981). The sand has been transported from southern Australia by longshore sediment transport systems (Boyd *et al.*

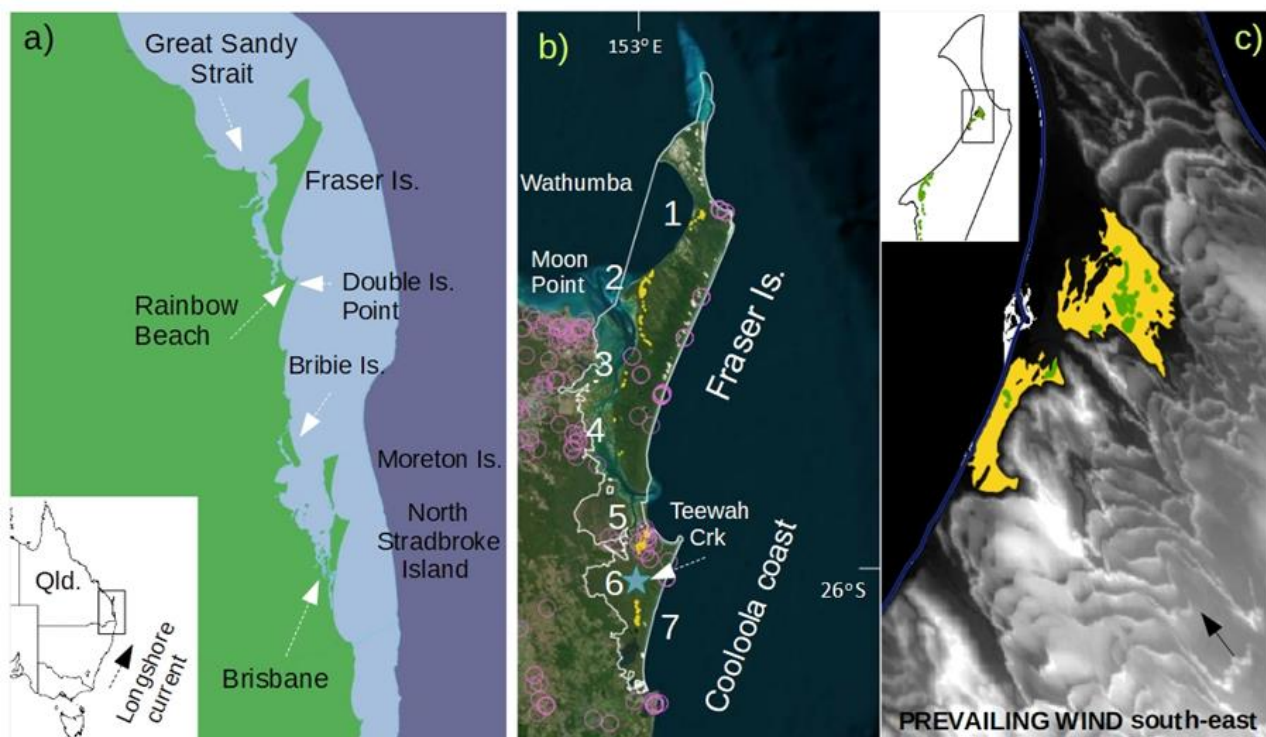


Figure 1. Geographical setting. a) south-east Queensland with features mentioned in text; light blue represents the continental shelf (Geoscience Australia 2009). b) Great Sandy Region showing the proposed Great Sandy World Heritage Area (white outline), patterned fens (yellow, numbered as in Table 1) and registered bore wells (pink circles; Queensland Government 2018). c) Elevation around a fen setting (black = sea level, white = parabolic dune crests to 130 m a.s.l.). The largest area of low drainage contains wet heath (yellow, northern area is 3 km wide) and pattering (green). Elevation data courtesy State of Queensland (Department of Science, Information Technology, Innovation and the Arts) 2011.

2008, Figure 1a) and deposited mainly during glacial periods throughout the last 750,000 years (Ward 2006, Figure 1c). During the last glaciation, which ended approximately 22,000 years ago, the sea level was around 120 m lower than at present (Petherick *et al.* 2008). Studies on adjacent sand islands show a mid-Holocene trend towards sclerophyllous vegetation, indicating shifts towards a drier climate (Barr *et al.* 2013) if not a shift in climatic variability (see examples in Moss *et al.* 2013).

The contemporary climate is subtropical with mean annual rainfall 1362 mm at Double Island Point (Station 040068, 25.93 °S, 153.19 °E, complete record from 1892 less 1992–95; Bureau of Meteorology 2017). On average, 25 % of the annual rainfall occurs between July and November. Twenty per cent of years receive <75 % of the long-term mean annual rainfall, and 20 % receive >125 %. Mean annual evaporation is equivalent to mean annual rainfall. The average annual temperature range is 18.7–24.2 °C.

The dunes are generally porous and contain chronosequences of humified podsols (Thompson 1992). Percolation of rainfall through them leads to rather acid groundwater (down to pH = 4) due to contact with acid organic compounds and lack of buffering capacity of the dune sand (Bayly *et al.* 1975). Substantial permanent streams exist on the dunes giving estimated discharges of, for example, 108 and 166 ML day⁻¹ from Coongul and Bogimbah Creeks, Fraser Island, and 874 ML day⁻¹ from Teewah Creek in the Cooloola region (Evans 1995). Groundwater also discharges from the bases of dunes (Coaldrake 1961) and supports peat development on adjacent poorly drained areas. Such areas are found on the western sides of both coastal dune systems.

EXTENT AND DISTRIBUTION OF FENS

A search of aerial photography available via Google Maps and What3Words.com was undertaken along the eastern seaboard of Australia to determine the full range of lowland patterned fens. A similar search was carried out around the global sub-tropical zone in order to identify any possible sub-tropical analogues elsewhere. The most striking and largest of the GSR patterned fens are concentrated along the western edges of both the Fraser Island and the Cooloola coastal sand dune systems, which comprise the study area (Figure 1b). There is also an isolated example associated with a parabolic dune system on Shoalwater Bay Military Reserve, 600 km north of

Brisbane. Small patterned areas occur on the sandy Moreton and North Stradbroke Islands, and there are isolated examples on the coast some 700 km south of Brisbane.

The study area has also been captured by digital ortho-rectified aerial photography (2010) with a pixel size of 0.25 m². Patterned areas can be readily identified by viewing these images at a scale of 1:10,000. All occur within previously-mapped ‘low wet heath’ vegetation (Regional Ecosystems 12.2.12 on the mainland and 12.2.15 on Fraser Island, DEHP 2013), and these regional ecosystems were explored for patterning. Historical (1950s) aerial photography for most of the patterned fens was sourced and rectified. Using all imagery, fen patterns were mapped at a scale not less than 1:10,000 and illustrated in Figures 2 and 3 according to the following categories: (1) irregular somewhat reticulate patterns of vegetated peat where the fraction of visible free water is between 10 % and 50 %; (2) free water with <50 % vegetation cover; and (3) linear ‘string mire-type’ patterning similar to that found in low-gradient temperate and boreal fen systems in both hemispheres (Gore 1983, Mark *et al.* 1995). The fens had not been burnt for several years prior to the imagery and, thus, the areal extent of ‘reticulate’ patterning would increase with post-fire visibility (illustrated in Figure 4). The mapping is supplied as a shapefile in the Supplementary Material, summarised in Table 1 and interpreted below.

All of the GSR patterned fens occur on the westward, inshore foot of parabolic dune systems. The western edges of Fraser Island’s fens are typically within tens of metres of the estuarine Moreton Bay, and the western edges of the Cooloola fens abut the Noosa River. Fourteen separate fens on Fraser Island (total area 3,540 ha) contain patterning and there are three examples covering a total area of 3,718 ha on the mainland at Cooloola. Ten percent of the Fraser Island fen area has reticulate patterning, with 65 ha of open water in total (Table 1). Patterned areas constitute the wettest end of the moisture budget of wet heath. Moon Point is the only example of linear ‘string mire’ patterning on Fraser Island. Cooloola fens contain 130 ha of reticulate patterning, 42 ha of linear patterning and a higher proportion of open water than the Fraser Island fens (120 ha). The Fraser Island and Cooloola fens differ in that their average area is much smaller on Fraser Island than on Cooloola (Table 1). While the dune systems have comparable volumes, substantial quantities of water discharge as creeks between the fens on Fraser

Island. Drainage from the Cooloola dune system is more diffuse, through fens to Teewah Creek and the Noosa River. This is likely to account for the greater areas of both open water and linear patterning on Cooloola relative to Fraser Island.

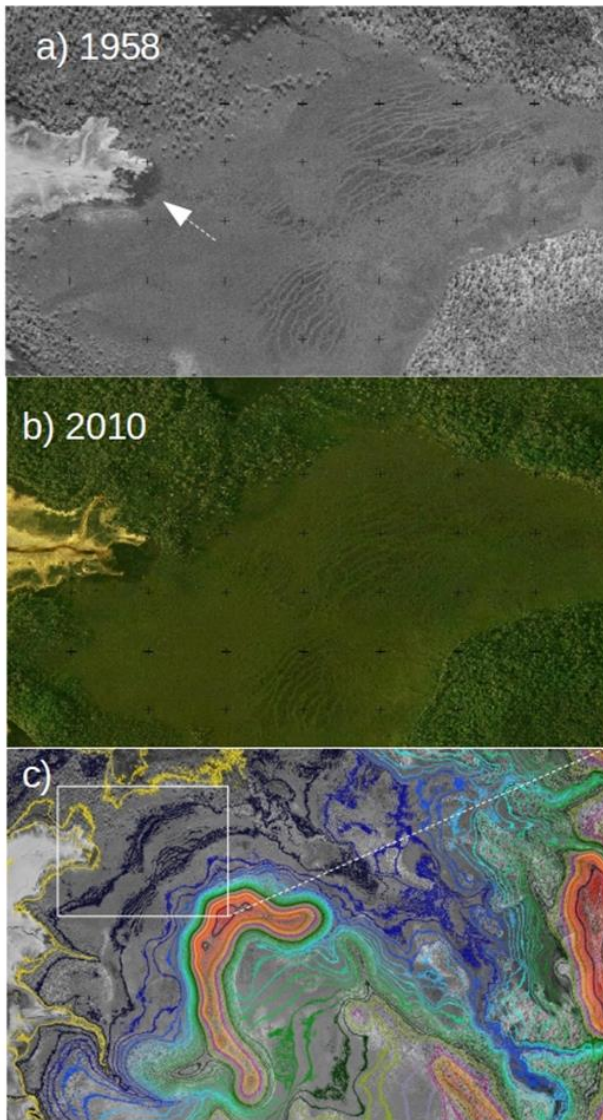


Figure 2. Aerial imagery of a fen with linear ‘string fen’ patterning adjoining a tidal mudflat near Rainbow Beach, Cooloola (153.046 °E, 25.953 °S). Tick marks on a) and b) represent 200 m intervals. Darker shades within the pattern represent open water. On panel c), altitude is represented by 1 m contours, where yellow represents 1 and 2 m a.s.l, dark blue 3 and 4 m a.s.l. etc. The top of the central sand ridge is at 50 m a.s.l. 2010 imagery and altitude data courtesy of State of Queensland (Department of Science, Information Technology, Innovation and the Arts) 2011.

SOURCE WATER

The primary source of water to the fens is groundwater discharge from the coastal sand dune systems (Coaldrake 1961, McDougall *et al.* 2017). Reeve & Fergus (1982) provide a description of the hydrology and water chemistry of the dune system: rainfall percolates through podsol chronosequences, becoming stained with organic matter and increasing in acidity to a mean pH of around 4.4. Acidity may be increased by oxidation of iron pyrites and maintained through lack of buffering capacity of the sand (Long *et al.* 1992). Then, through podsolisation, the fluid loses organic matter, colour, aluminium and iron, eventually becoming ‘white water’ of a deeper aquifer. The chronosequences differ slightly between the Fraser Island and Cooloola dune systems (Thompson 2004). At Cooloola, suspected connectivity between multiple aquifers (Evans 1995) has since been confirmed (McDougall *et al.* 2017). The complex hydrology described by McDougall *et al.* (2017) is likely to apply also to Fraser Island. Residence times of water within the dune systems are unknown.

On the better-studied sandy Stradbroke Island, recharge rates average approximately 34 % of annual precipitation (with temporal and spatial variation, Leach & Gallagher 2013). On Bribie Island, lake discharges have been estimated at eight times precipitation (Sadat-Noori *et al.* 2016).

PATTERNING

An understanding of pattern development from northern *Sphagnum* mires provides a conceptual basis for studies of patterning in the GSR systems, albeit with a different ecosystem engineer (the restiad *Empodisma minus* as opposed to *Sphagnum* spp.). The key characteristic of mire patterning is the distribution of pools of open water demarcated by elevated, saturated vegetated ridge or hummock features. Irregular, non-linear pools of free water can occur where the influx of water exceeds efflux (e.g. Foster *et al.* 1988). Broadly linear string-fen formations can occur with greater slope (Heinselman 1965, Foster *et al.* 1988, Mark *et al.* 1995). Both patterns exist in the study area although the irregular ‘reticulate’ pattern observed in GSR mires is highly distinctive and more clearly reticulate in its morphology, which resembles that of sub-arctic and arctic polygonal mires (Yurkovskaya 2005), than is typical of non-linear patterning elsewhere in both northern and southern hemispheres (e.g. Goode & Lindsay 1979, Ivanov 1981). This is perhaps one of

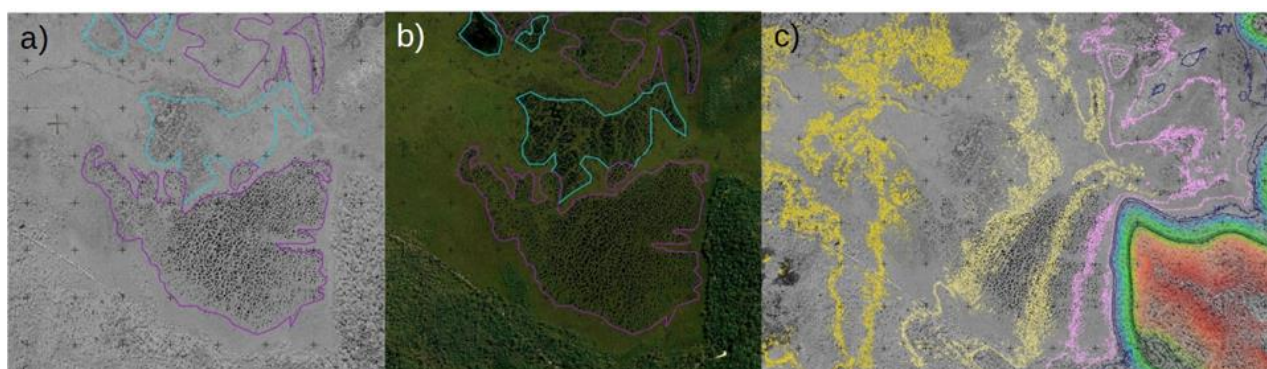


Figure 3. Aerial imagery of a small fen with irregular 'reticulate' patterning near Moon Point, Fraser Island (153.06 °E, 25.215 °S). Tick marks on a) and b) represent 200 m intervals. Darker shades within the pattern represent open water. On panel c), altitude is represented by 1 m contours, where yellow represents 1 m and 2 m a.s.l., dark blue 3 and 4 m a.s.l., etc. The top of the south-eastern sand ridge is at 60 m a.s.l. 2010 imagery and altitude data courtesy of State of Queensland (Department of Science, Information Technology, Innovation and the Arts) 2011.

the most significant features of the GSR peatlands within a global context (Figures 2 and 3, Table 1).

Studies of pool development on patterned mires in Sweden (Foster & Fritz 1987), Canada (Foster *et al.* 1988) and Scotland (Charman 1994, Belyea & Lancaster 2002) suggest that the initial stage of permanent pool formation is a small area of surface water in a poorly drained area. In the case of the GSR fens, initial conditions (late Pleistocene) appear lacustrine (Moss *et al.* 2016). Low slope permits stagnation where dissolved oxygen content can decline, becoming less conducive to plant growth. Plants may grow on or above pool edges but not decompose after dying, with peat accumulating faster outside a pool than within it (Foster *et al.* 1988). As vegetation grows, peat accumulates, the pool edge grows higher and the pool itself progressively deepens (e.g. Belyea & Lancaster 2002). Relative rates of peat accumulation and decomposition, water chemistry and hydrostatic pressure may all influence patterning (e.g. Belyea & Lancaster 2002). Indeed, lateral flow and hydrostatic pressure can be influenced by the physical properties of the patterns (Couwenberg & Joosten 2005), which may be stable at the multi-century scale. After thousands of years, pools of open water may coalesce (Foster & Fritz 1987, Foster *et al.* 1988) and possibly represent the oldest portions of a mire (e.g. Mark *et al.* 1995, Belyea & Lancaster 2002).

Catchment area, surface slope and depth of peat also influence hydrology, which has been invoked to explain observed patterns in boreal mires (White & Payette 2016). Drainage can promote the development of linear pools aligned perpendicular to the direction of flow (Heinselman 1965, Glaser *et al.*

1981, Foster & King 1984, Foster & Fritz 1987).

These processes operate for centuries if not millennia. The surface patterning of GSR fens is relatively stable (at least over half a century, e.g. Figure 2). The base of the acrotelm studied by Krull *et al.* (2004) was 68 cm below the mire surface and aged at around 270 years. Peat from both Rainbow Beach and Moon Point (Figure 1b) has been dated as coinciding with the Holocene (around 12,000 years before present, Krull *et al.* 2004 and Moss *et al.* 2016, respectively). Wathumba Fen appears to be some 8,000 years younger, and differs from the latter fens in not having linear string-fen patterns (Table 1).

VEGETATION

Lowland patterned fens occur on acidic soils which are deficient in many nutrients (von Stieglitz *et al.* 1963). These support botanically diverse (e.g. Westman 1975) vegetation with affinities to both shrublands and heathlands. Further details are provided by Coaldrake (1961), Griffith & Wilson (2007), Griffith *et al.* (2008) and DEHP (2013). Peatlands are often regarded as forming part of the 'wet heath' spectrum but the presence of a peat deposit separates such systems from wet heath habitat and establishes them as distinct peatland habitat. Fen peatlands occupy the minerotrophic portion of the peatland spectrum. Despite being a distinct habitat type, peatland systems often support a small subset of wet heath flora on the drier parts of the microtopography that is such a characteristic feature of many peatland types.

Visits to most of the Great Sandy Region fen

Table 1. Areal extent (ha) of: wet heath vegetation containing patterned fens of the GSR as illustrated in Figure 1c (RE = Regional Ecosystem, Queensland Herbarium 2019) and the minimum area of irregular/reticulate patterning, linear patterning and open pools without surface vegetation (illustrated in Figures 2 and 3).

Name (# Figure 1b)	Dominant adjacent RE	RE (ha)	Minimum area (ha) of irregular patterning (n, range)	Minimum area (ha) of linear patterning (n, range)	Minimum area (ha) of free water
Wathumba North (1)	12.2.6,7,9	12.2.15 (636)	29.56 (15, 0.33-7.95)		20.0 (9, 0.39-9.83)
Wathumba South (1)	12.2.6,7,9,14 ocean	12.2.15 (275)	12.88 (7, 1.35-3.07)		0.06 (1)
Moon Point main (2)	12.2.6,7,9	12.2.15 (1452)	219.11 (32, 0.2-36.7)	79.36 (5, 1.7-63.6)	44.54 (12, 0.2-13.38)
Moon Point a (2)	12.2.6,7	12.2.15 (196)	8.18 (7, 0.31-4.7)		
Moon Point b (2)	12.2.6,7	12.2.15 (169)	37.59 (8, 0.91-11.04)		
Moon Point c (2)	12.2.6,9	12.2.15 (49)	13.48 (1)		
Moon Point d (2)	12.2.9	12.2.15 (51)	4.59 (3, 0.67-2.07)		
Moon Point e (2)	12.2.6,9	12.2.15 (108)	9.51 (5, 0.33-3.78)		
Wangoolba N (3)	12.2.6,7,9	12.2.15 (115)	4.14 (1)		0.15 (1)
Wangoolba mid (3)	12.2.6,9	12.2.15 (42)	1.26 (1)		
Wangoolba S (3)	12.2.6, 12.1.3	12.2.15 (97)	9.64 (8, 0.26-5.36)		
Fraser Is South (4)	12.2.6,7, 12.1.3	12.2.15 (201)	2.33 (4, 0.22-0.96)		
Fraser Is South (4)	12.2.6,9	12.2.15 (87)	1.60 (1)		
Fraser Is South (4)	12.2.6, 12.1.3	12.2.15 (62)	0.84 (1)		
Rainbow Beach (5)	12.2.5, 9	12.2.12 (1424)	68.0 (43, 0.23-7.57)	24.21 (2, 5.77-15.1)	22.26 (8, 0.15-8.12)
Cooloola North (6)	12.2.6,9	12.2.12,13 (1410)	42.69 (8, 0.22-13.57)	22.05 (4, 2.43-13.6)	18.69 (6, 0.57-10.47)
Cooloola South (7)	12.2.6,9	12.2.12 (884)	20.61 (6, 1.34-7.73)		80.53 (15, 0.15-55.8)

complexes in 2011 yielded a total list of just 28 plant species with the average number of species per fen only 14. All fens were dominated by *Empodisma minus* (Restionaceae) and had the following ten other species in common: the pyrescent shrubs *Leptospermum livesidgei* (Myrtaceae) and *Banksia robur* (Proteaceae), the heathy shrubs *Epacris microphylla*, *Sprengelia sprengelioides* (Ericaceae) and *Hibbertia salicifolia* (Dilleniaceae). Common sedges (Cyperaceae) were *Gahnia sieberiana* around the mire margins and *Baumea rubiginosa*, *Baumea teretifolia* and an unidentified sedge around the edges of pools. The hemiparasitic vine *Cassytha glabella* (Lauraceae) was ubiquitous. The less common *Utricularia lobata* (Utriculariaceae) occurs in pools and obtains nutrients by trapping and digesting aquatic microfauna. The carnivorous *Drosera binata* and *Drosera peltata* (Droseraceae) target larger airborne and surface prey respectively. No exotic species were encountered.

Most surviving Northern Hemisphere peatlands are ombrotrophic bogs dominated by *Sphagnum* spp. (Rydin & Jeglum 2006). Fen systems dominated by Cyperaceae (sedges) were once extensive on lowland floodplains, but the largest surviving examples of fen

habitat are now the large string fens within the Boreal Region. Southern Hemisphere peatlands are also dominated by *Sphagnum* species in the far south, while in temperate or sub-tropical regions peat may be formed not only by *Sphagnum* spp. but also by sedges or, uniquely to the Southern Hemisphere, Restionaceae (restiads) (Whinam *et al.* 2003). The role of the restiad species *Empodisma minus* as an ecosystem engineer in autogenic fen–bog transitions (as opposed to *Sphagnum* spp. in the Northern Hemisphere) has been established elsewhere in the Antipodes (Hodge & Rapson 2010). It is a clonal resprouter with high lignin content that impedes drainage, reduces evaporation from the mire, releases organic acids, and has allelopathic properties. Its root mass is negatively geotropic (i.e. grows upwards into the atmosphere to access air and nutrients; see also Campbell *et al.* 1995) with high moisture retention capacity. Its roots were observed growing up the stems of small shrubs (such as *Leptospermum livesidgei*, Figure 4) in fens throughout the GSR, behaviour indicative of anoxic water.

Fire has been part of the environment of the fen vegetation for millennia (Moss *et al.* 2016). Pyriscence is known in other *Leptospermum* and



Figure 4. A non-linear pool near the mouth of Wanggoolba Creek (Fraser Island) which was burnt on 01 June 2011. The bases of the two *Leptospermum livesidgei* shrubs (bottom right) are covered in negatively geotropic *Empodisma minus* roots.

Banksia species (Clarke *et al.* 2010) and in nearby wet heath the abundance of *E. minus* stems has been documented to increase after fire (McFarland 1988a). Fire events appear to have become less frequent since indigenous land use was replaced by European forms of land management (Moss *et al.* 2016).

Occasional trees belonging to the genera *Eucalyptus*, *Lophostemon* and *Melaleuca* (all Myrtaceae) can occur within, but proximate to, the internal (saturated) margins of mires. This suggests that, at times, the water table has lowered sufficiently to provide conditions favouring their establishment. A comparison of remotely sensed imagery (1958 and 2010) shows that changes in woody vegetation around mire margins can occur, but that the vegetation patterns on the fens themselves have remained remarkably stable (Figures 2, 3).

VALUES

Carbon sequestration and storage

The value of peatlands for carbon sequestration is well established (e.g. Yu *et al.* 2010). Soils at the drier end of the ‘wet heath’ spectrum are naturally acidic and contain >10 % organic matter (Griffith *et al.* 2008). The total organic carbon content of the GSR peat sample analysed by Krull *et al.* (2004) was 22–40 %, depending on depth (to 2.5 m, see also Moss *et al.* 2016).

Potential to reveal environmental history

The partially decomposed vegetation that comprises peat can include material that is suitable for radiocarbon dating (e.g. Bauer & Vitt 2011) and numerous other dating techniques (see examples in Charman *et al.* 2013). Fire history can be reconstructed from charcoal (e.g. Pitkänen *et al.* 1999). The presence and positions of phytoliths in peat cores can reveal the vegetation history of a site (e.g. Taffs *et al.* 2006), while pollen can provide information about the broader region over time (e.g. Moss *et al.* 2016). Broad-scale climate patterns can be inferred from trapped dust (e.g. Petherick *et al.* 2008) and sedimentation patterns can reveal history including marine transgressions (e.g. Newnham *et al.* 1995). Thus, aspects of the geomorphological, hydrological, climatic and sea level history of the GSR, as well as details of human influence throughout the Holocene (e.g. Moss *et al.* 2013), can be informed through knowing the age, origin and history of the patterned fens. It follows that the patterned fens of the study area could reasonably be expected to inform contemporary (and future) fire management (Moss *et al.* 2012), coastal management

(Brooke *et al.* 2008), water management and ecosystem recovery (see Anon. 2006) as well as our understanding of the sensitivity and resilience of peaty ecosystems to climate change (Moss *et al.* 2016) and broader management of the Ramsar and World Heritage Area (Shapland *et al.* 2012).

Habitat for rare fauna

Records of fauna from GSR fens were identified by intersecting areas mapped as Regional Ecosystems 12.2.12 on the mainland and 12.2.15 on Fraser Island (DEHP 2013) with all listed species records from the WildNet database (Queensland Department of Science Innovation Technology Innovation and the Arts, unpublished). A large proportion of these are listed under Australian legislation and the IUCN Red List criteria (IUCN 2017) indicated in parentheses: all four ‘acid frogs’ of the region *Crinia tinnula* (Vulnerable B2ab(ii,iii,iv,v)), *Litoria cooloolensis* (Endangered B1ab(iii)), *L. freycineti* (Vulnerable B2ab(ii,iii,iv,v)) and *L. olongburrensis* (Vulnerable B1ab(ii,iii,iv)+2ab(ii,iii,iv)); the false water-rat *Xeromys myoides* (Vulnerable B2ab(ii,iii,v)); two fish species *Nannoperca oxleyana* (Endangered A1ce+2c) and *Pseudomugil mellis* (Endangered A1acde+2cde) plus the ornate rainbow fish *Rhadinocentrus ornatus* whose listing under Australian legislation is supported by Page *et al.* (2004). The birds Lewin’s Rail (*Lewinia pectoralis*), Southern Emu-wren (*Stipiturus malachurus*) and Eastern Ground Parrot *Pezoporus wallicus wallicus* are all listed as Least Concern with decreasing trends (IUCN 2017). The latter species, also seen near Moon Point in 1939, had by then been in notable decline for some time (N.L.R. 1939).

The only targeted study of fauna is that of Hobson & Head (1996) who surveyed three fens and recorded the declining and endangered Eastern Curlew (*Numenius madagascariensis*, A2bc+3bc+4bc), a migrant from boreal moorlands which is named in multiple international agreements.

Other recorded species are indicative of swampy habitat: grassland melomys (*Melomys burtonii*), Australian swamp rat (*Rattus lutreolus*), bush rat (*Rattus fuscipes*), pale field rat (*Rattus tunneyi*), common planigale (*Planigale maculata*), northern brown bandicoot (*Isodon macrourus*); slender yabby (*Cherax dispar*), long-armed prawn (*Macrobrachium tolmerum*) and a shrimp *Caridina* sp.; the Blue Quail (*Coturnix chinensis*), Tawny Grassbird (*Megalurus timoriensis*) and Red-backed Fairywren (*Malurus melanocephalus*).

Like ‘blackwater’ discharge from boreal fens, groundwater discharge from dune systems is likely to contain high levels of dissolved iron which underpin

a healthy food chain (Krachler *et al.* 2019) and provide ecological services for migratory birds, adjacent low-salinity-tolerant mangrove communities and estuarine fish nurseries (e.g. Silva *et al.* 2012). The fens also provide habitat for invertebrates, including crustacea (living in acid waters, FIWHASAC 2004a).

Current condition

The current condition of the patterned fens of the GSR might be qualitatively described as apparently excellent. Based on what is known at present, the fens of the GSR appear largely unaffected by any of the potential threats summarised in the Introduction. Nonetheless, two markers of the change from indigenous to European occupation have been noted: firstly, a clear decrease in charcoal particles with a concurrent decline in pollen of shrubs; and secondly the appearance of pollen from post-European plantations of *Pinus* on the mainland (Moss *et al.* 2016). Furthermore, processes external to the fens (such as groundwater abstraction and climate change) have significant potential to result in negative effects on habitat condition, and these are discussed in turn below.

THREATS

Groundwater abstraction

Groundwater abstraction is an explicit threat for the fens at Cooloola (Stockwell *et al.* 2004, McDougall *et al.* 2017), with potential effects analogous to the drainage commonly experienced by peatlands around the world (e.g. Vasander *et al.* 2003) and numerous peatlands within Australasia (Whinam *et al.* 2003). The often irreversible negative implications have been reviewed by Holden *et al.* (2004) and include increases in bulk density of the peat, decomposition, leaching and erosion. Within patterned fens, vertical water exchange is thought to be more important than lateral water movement, with retreat of the water table below the mire surface resulting in increased peat decay and potential loss of the characteristic patterning (Whittington & Price 2006).

Groundwater levels may predictably decline with abstraction (e.g. Spring 2005). Subsequent desiccation and uncontrolled fire has already resulted from abstraction in some Australian peatlands (Blake *et al.* 2009). The current study area contains around 20 registered boreholes within the dune systems (Figure 1b; Queensland Government 2018). Water is also abstracted from a creek discharging into one of the fens (Evans 1995). Water for the township of Rainbow Beach is sourced from the dune system

immediately above the patterned fen adjoining that town (Evans 1995, Anon. 2006). Some boreholes access freshwater below mean sea level. Effects on the fens are unknown. However, residents of several towns within the GSR have already noticed increased salinity in freshwater boreholes, and groundwater abstraction is set to increase further as the region's human population is expected to grow by at least 1.6 % p.a. to 2031 (Queensland Treasury 2011). Saltwater intrusion into coastal freshwater aquifers has been chemically confirmed (Larsen & Cox 2011) and attributed to both tidal characteristics and lowering of the water table as a result of (freshwater) abstraction. While the latter process may be manageable to some degree, lowering the freshwater hydraulic head below a key threshold would result in irreversible consequences (e.g. Katic & Quentin Grafton 2011). Should the Great Sandy World Heritage Area be extended as proposed, incorporating aquifer management into the relevant management system is both defensible and highly desirable for these groundwater dependent ecosystems.

Aquifer response to projected human water demands has been modelled for the Cooloola region (Evans 1995) albeit utilising assumed permeability and a narrow range of recharge rates. A subsequent framework for management of water obtained from relevant aquifers is embodied in a statutory plan (Anon. 2006) with objectives including “to maintain subartesian water discharge to support wetlands and other groundwater-dependent ecosystems” and “to ensure reliable and secure water entitlements...”. A separate purpose of the plan is to provide a framework for reversing degradation of water-dependent ecosystems associated with abstraction. Its provisions include a requirement that cumulative impacts of abstraction should be considered, with monitoring in the case of Cooloola.

Cooloola's fens occur along the eastern bank of the lower Noosa River and its main tributary Teewah Creek (Figure 1b) and are significant contributors to baseflow in those watercourses (Evans 1995, McDougall *et al.* 2017). Continuous monthly flow rate and rainfall data (2002–16) are available for Teewah Creek (Streamflow gauge 140002A at 5.32 m a.s.l., 26° 03' 25.8" S 153° 02' 33.5" E; State of Queensland 2017). This provides a means to assess baseflow. Mean annual rainfall is around 1750 mm. The stream is permanent, with height (stage) and flow responsive to recent rainfall (Figure 5). It is evident that streamflow is most likely to increase in response to rainfall when flow exceeds 1145–1165 ML month⁻¹. Below this flow rate, any monthly rainfall < 110 mm does not prevent further decline in

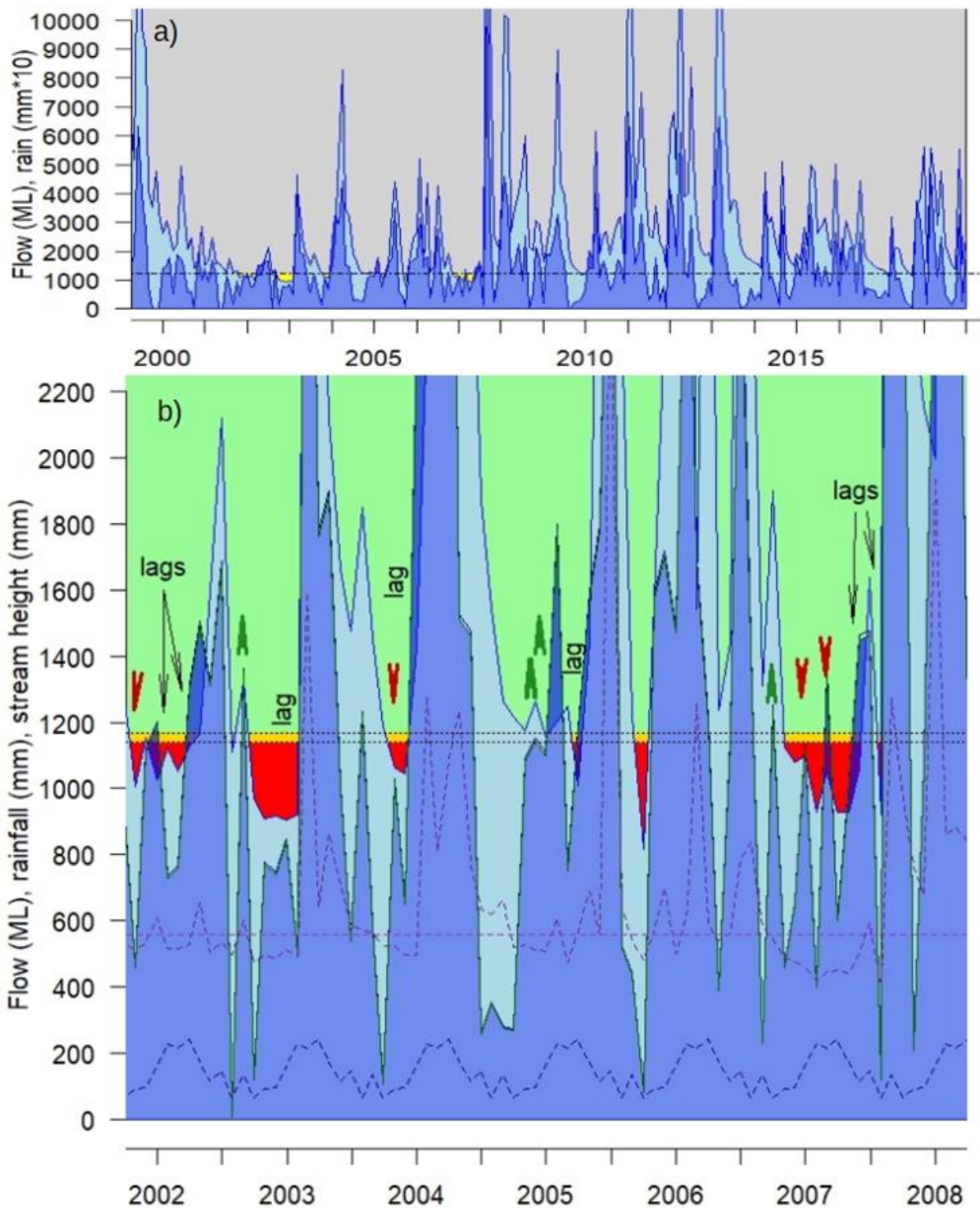


Figure 5. Baseflow estimation from the Teewah Creek stream gauge. Monthly streamflow (light blue) and rainfall (medium blue, $\text{mm} \times 10$) for Teewah Creek: a) 1999–2019 and b) July 2001 to June 2008. Stream height is indicated by the dashed purple line; the horizontal dotted purple line represents the tenth percentile of stream heights when flow exceeds $1160 \text{ ML month}^{-1}$. The lowest dashed line represents average monthly rainfall (mm). Recharge deficits are presented (yellow) as occurring when rainfall is unlikely to increase streamflow. Arrows indicate changes in whether increased streamflow is expected after a rainfall event when flows are above or below apparent balance. Appreciable temporal lags between rainfall and increased streamflow are indicated, and commence during periods of deficit.

flow; examples include early 2002 and early 2007 (both relatively dry ends to relatively dry wet seasons). Aquifer deficit can again be inferred later in those years, when lag times between high rainfall months and creek flow response are pronounced (Figure 5). When streamflow exceeds around 1160 ML month⁻¹ (the best available baseflow value for the fens) stream height at the gauge exceeds 0.56 m for 90 % of the time. This approach (potentially with improvements) could be employed elsewhere.

Sand mining

Minerals such as ilmenite, rutile, zircon and silicon are present within the Fraser Island and Cooloola sands (e.g. Sinclair & Corris 1994). While connections between mined sand and the underlying aquifer may be easily established (e.g. Viswanathan 1990), so may the relationship between proposals to mine these minerals from the GSR and their replacement with two separate National Parks (Fraser Island and Cooloola, e.g. references in Sweett 2008). Sand mining activities did occur intermittently in the south-east of Fraser Island and on the nearest mainland (Inskip Point) in the 1970s. It is unknown what direct effect this may have had on the fens - probably extremely little (if any) compared to the mine-altered hydrology witnessed on North Stradbroke Island (e.g. Cox *et al.* 2011) or, indeed, what could have been lost. All of the GSR fens are presently located on National Park or unallocated State land that is unlikely to be directly developed in this way.

Fire

Extensive areas of peat may burn for decades (Ellery *et al.* 1989) with substantial losses of below-ground carbon (Zoltai *et al.* 1998). Fire has compromised the (catotelm) peat layers of various sites throughout the world (Pitkänen *et al.* 1999, Posa *et al.* 2011), is a major cause of carbon emissions from western boreal peatlands (Turetsky *et al.* 2002), and may result in the release of chemicals that are harmful to humans (Blake *et al.* 2009). However, unlike the boreal and sub-arctic peatlands of North America which burn at intervals of centuries (Zoltai *et al.* 1998), a frequency of fire closer to that of ENSO (El Niño - Southern Oscillation) cycles has been recommended for wet heath in south-east Queensland (Watson 2001), although it is important to highlight the fact that peatland and wet heath are not synonymous and that the former may require a very different management regime from that considered appropriate for wet heath. Charcoal has been recorded throughout peat sampled from GSR patterned fens (Krull *et al.* 2004, Moss *et al.* 2012, Shapland *et al.* 2012),

demonstrating that fire was a common feature of the pre-European landscape, while subsequent peat accumulation indicates that the habitat was at least capable of tolerating such a regime. Further work is required to determine the optimal fire regime for the distinctive features of these peatland systems.

The GSR fens experience high inter-annual rainfall variability and high evaporation rates, and are adjoined by flammable sclerophyllous vegetation communities (Srivastava *et al.* 2013). While highly adapted to the unique hydrological environment, the fen vegetation is also flammable. Recommended fire-return intervals range from a maximum of twenty years to allow for shrubs that evolved as (fire) obligate seeders (Queensland Herbarium 2019) to a minimum of 7–8 years for fauna, especially birds (McFarland 1988b, Watson 2001).

The most fire-sensitive peat occurs where the edge of a mire continues under sand; the largest losses of peat are likely to occur upslope and sub-surface from this edge. Fire-related threat is of greatest concern during periods of water deficit, when peat is most likely to burn. The threat can be mitigated by maintaining the highest possible water level, with any deliberate burning (e.g. to increase ground parrot habitat) restricted to when the ground is wet (Watson 2001). Indeed, current fire management aims to address biodiversity and ecosystem protection concerns by burning wet heath at intervals of approximately ten years, shortly after rain (C. Lawton, personal communication). Further research into peatland processes and their associated biodiversity is clearly warranted in order to determine whether the current regime is optimal.

Peat extraction

The effects of peat or moss harvesting on wetland functions vary with extraction rate and method, but can tend towards complete loss of the wetland and associated environmental services (e.g. Winkler & Dewitt 1985). Although at small scale relative to similar activities in Europe, peat extraction has occurred at various locations within Australasia. The story of the largest restiad-dominated upland mire in mainland Australia (Wingecarribee Swamp, ~ 650 ha) ends with direct and indirect consequences for natural values (Whinam *et al.* 2003). The current threat of peat extraction in the GSR is low.

Climate change

Climate change is undoubtedly an issue with potential to have major impacts on the peatlands of the GSR but the threats are, like many assessments of climate change, in the nature of predictions or projections rather than demonstrable current effects.

The implications of climate change for peatlands have been addressed by Parish *et al.* (2008) and Strack (2008), amongst others. While an increase in ambient temperature (e.g. global warming) could be favourable to vegetative growth and carbon accumulation in temperate mires (see Zhang *et al.* 2018), it may not be at lower latitudes where increased temperatures are predicted to raise the decomposition rate over and above the increased growth rate of plants (Gallego-Sala *et al.* 2018). This conclusion draws upon data from many peatlands including the Moon Point fens on Fraser Island (Moss *et al.* 2016). Additional climate-related threats that may be imposed upon the fens of the GSR include increased evaporation, decreasing rainfall, increased drought intensity and rising sea level. The frequency and intensity of fire may also increase (Williams & Crimp 2012).

At Double Island Point (Figure 1a), average annual rainfall over the 60 years to 1952 was 1394 mm. For the period 1953–2016 (minus the years with incomplete data 1992–95) this decreased to 1340 mm (Bureau of Meteorology 2017). The same trend is occurring throughout southeast Queensland (Williams & Crimp 2012). The monthly average of daily maximum temperature for 1938–1972 was 23.6 °C, whereas it was 24.8 °C for 1973–2015. Since 1960, the study area has warmed by around 1 °C and received around 5 % less yearly rainfall. These values, together with data for pan evaporation, are not unique to the GSR and the trends are expected to continue even under ‘best-case’ scenarios (Williams & Crimp 2012). The amount of water input to the system is decreasing while evaporation is increasing. Such declines of water moving into and through the system may facilitate oxidation and decomposition of upper peat layers (Leiffield *et al.* 2016), and the same applies to the threat of groundwater abstraction already discussed.

Given the dependence of the GSR patterned fens on a rainfall-charged aquifer, the spatial distribution and rate of peat formation is likely to change in response to altered climate (Hilbert *et al.* 2000). An increase in temperature may result in peat desiccation, decomposition, increase in acidity, increased oxidation of iron pyrite and release of sulphurous compounds into the atmosphere (e.g. van Dam & Beltman 1992). The intensity and frequency of fire may also increase (e.g. Williams & Crimp 2012). A key determinant of peat accumulation is net primary productivity, which is responsive to ambient temperature and moisture availability. This renders the system sensitive to climate change (Charman *et al.* 2013) with potential for the fens to change from a net carbon sink to a net source (Rennermalm *et al.*

2010). However, peatlands possess a self-regulation mechanism whereby changes in species composition and surface patterning can provide resilience to environmental change over millennial timescales. It is not yet known how the GSR fens may respond over time, but evidence of self-regulatory behaviour is likely to emerge as environmental pressures increase and should be looked for in any future survey or monitoring programmes (e.g. Barber 1981).

Global sea level rise is inevitable (Hu & Deser 2013) and expected to affect groundwater in south-east Queensland (e.g. Surawski *et al.* 2005). The GSR patterned fens may be naturally influenced by seawater from below (Moss *et al.* 2016), salty water being denser than freshwater. However, when seawater overtops non-saline peatland, salt-intolerant species may be negatively affected to the point of compromising peatland recovery and promoting erosion (Emond *et al.* 2016). Sensitivities of sand-island aquifers to seawater encroachment are known (e.g. Hodgkinson *et al.* 2007, Jackson 2007).

During the mid-Holocene (7000–6000 years ago), the sea level of south-east Queensland was around 1 m higher than at present (Lewis *et al.* 2013). Fens may have started to develop after the subsequent fall in sea level (during the second phase identified by Moss *et al.* 2016) and not been inundated by saltwater since. Millennial-scale recovery of transgressed peatlands has been recorded in New Zealand (Newnham *et al.* 1995). Sensitivity of the GSR fens to the sea level rise that is expected now can be informed by altitude. Airborne laser-derived elevation (DEM) data with vertical accuracy approximately 0.22 m shows that the fens on both Fraser Island and the adjacent mainland are generally 1–8 m above current high tide and most are within the altitude range 2–6 m a.s.l. (Figures 2 and 3). The most sensitive are likely to be those that directly adjoin marine vegetation or the tidal Noosa River.

CONCLUSION

Although patterned mires are extensive in the Northern Hemisphere, rather limited occurrences have been noted south of the Equator, in moist temperate regions of southern South America and the Antipodes (Mark *et al.* 1995). The GSR patterned fens are actively growing and apparently the most concentrated examples of a groundwater-dependent ecosystem type that is unique to the sub-tropical seaboard of eastern Australia. Despite their depauperate botanical assemblages, they support several vulnerable and endangered vertebrates. There is little doubt that attention to aquatic invertebrates

will reveal unique adaptations if not behaviours for the characteristically acidic conditions of these unusual habitats, and possibly also new insights on invertebrate speciation through the Holocene. Thus, the fens of the GSR emerge as very special parts of Australia's natural heritage which have been almost wholly overlooked and appear still to be in very good condition, although the effects of the most recent human interventions have yet to be assessed in detail. Enough hydrological information exists to identify water abstraction as a key threat (McDougall *et al.* 2017) though this can be regarded as manageable (e.g. FIWHASAC 2004b). Given the World Heritage status of these freshwater and adjacent systems, there is a compelling argument for action to ensure that the GSR fens are provided with both legislative mechanisms to secure their protection and an appropriate management regime to maintain their structure and function.

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AUTHOR CONTRIBUTIONS

RF conceived the study, conducted the GIS analyses, undertook the fieldwork and wrote the first draft of this article. RL determined the wider distribution of patterned fens, wrote parts of later drafts, and commented on all versions of the manuscript.

REFERENCES

- Anon. (2006) *Water Resource (Mary Basin) Plan 2006*. Subordinate Legislation 2006 No. 192. Online at: <https://www.legislation.qld.gov.au/view/pdf/inforce/current/sl-2006-0192>, accessed 31 July 2018.
- Barber, K.E. (1981) *Peat Stratigraphy and Climate Change: A Palaeoecological Test of the Theory of Cyclic Peat Bog Vegetation*. A.A. Balkema, Rotterdam, 242 pp.
- Barber, K., Dumayne-Peaty, L., Hughes, P., Mauquoy, D. & Scaife, R. (1998) Replicability and variability of the recent macrofossil and proxy-climate record from raised bogs: field stratigraphy and macrofossil data from Bolton Fell Moss and Walton Moss, Cumbria. *Journal of Quaternary Science*, 13, 515–528.
- Barr, C., Tibby, J., Marshall, J.C., McGregor, G.B., Moss, P.T., Halverson, G.P. & Fluin, J. (2013) Combining monitoring, models and palaeolimnology to assess ecosystem response to environmental change at monthly to millennial timescales: The stability of Blue Lake, North Stradbroke Island, Australia. *Freshwater Biology*, 58, 1614–1630.
- Bauer, I.E. & Vitt, D.H. (2011) Peatland dynamics in a complex landscape: Development of a fen-bog complex in the sporadic discontinuous permafrost zone of northern Alberta, Canada. *Boreas*, 40, 714–726.
- Bayly, I.A.E., Ebsworth, E.P. & Hang Fong Wan. (1975) Studies on the lakes of Fraser Island, Queensland. *Australian Journal of Marine and Freshwater Research*, 26, 1–13.
- Belyea, L.R. & Lancaster, J. (2002) Inferring landscaped dynamics of bog pools from scaling relationships and spatial patterns. *Journal of Ecology*, 90, 223–234.
- Belyea, L.R. & Malmer, N. (2004) Carbon sequestration in peatland: patterns and mechanisms in response to climate change. *Global Change Biology*, 10, 1043–1052.
- Blake, D., Hinwood, A.L. & Horwitz, P. (2009) Peat fires and air quality: Volatile organic compounds and particulates. *Chemosphere*, 76, 419–423.
- Boyd, R. (2004) River of sand - a geological perspective on Fraser Island and the GSR. Online at: http://fido.org.au/Conferences/2004_FI_2020/papers/Ron%20Boyd.pdf, accessed 31 July 2018.
- Boyd, R., Ruming, K., Goodwin, I., Sandstrom, M. & Schröder-Adams, C. (2008) Highstand transport of coastal sand to the deep ocean: A case study from Fraser Island, southeast Australia. *Geology*, 36, 15–18.
- Brooke, B., Lee, R., Cox, M., Olley, J. & Pietsch, T. (2008) Rates of shoreline progradation during the last 1700 years at Beachmere, southeastern Queensland, Australia, based on optically stimulated luminescence dating of beach ridge. *Journal of Coastal Research*, 243, 640–648.
- Bureau of Meteorology (2017) *Climate Data Online*. Australian Government Bureau of Meteorology,

- Melbourne. Online at: <http://www.bom.gov.au/climate/data/>, accessed 04 Nov 2017.
- Campbell, E.O., Sharpe, P. & Windolf, J.F.P. (1995) The significance of *Empodisma minus* (Restionaceae) in mires of eastern Australia, with particular reference to the coastal marshlands of S.E. Queensland. *New Zealand Botanical Society Newsletter*, 42, 8–11. Online at: <http://www.nzbotanicalsociety.org.nz/newsletter/NZBotSoc-1995-42.pdf>, accessed 29 Jly 2019.
- Charman, D.J. (1994) Patterned fen development in northern Scotland: developing a hypothesis from palaeoecological data. *Journal of Quaternary Science*, 9, 285–297.
- Charman, D.J., Beilman, D.W., Blaauw, M., Booth, R.K., Brewer, S., Chambers, F.M., Christen, J.A., Gallego-Sala, A., Harrison, S.P., Hughes, P.D.M., Jackson, S.T., Korhola, A., Mauquoy, D., Mitchell, F.J.G., Prentice, I.C., van der Linden, M., De Vleeschouwer, F., Yu, Z.C., Alm, J., Bauer, I.E., Corish, Y.M.C., Garneau, M., Hohl, V., Huang, Y., Karofeld, E., Le Roux, G., Loise, J., Moschen, R., Nichols, J.E., Nieminen, T.M., MacDonald, G.M., Phadtare, N.R., Rausch, N., Sillasoo, Ü., Swindles, G.T., Tuittila, E.-S., Ukonmaanaho, L., Väliranta, M., van Bellen, S., van Geel, B., Vitt, D.H. & Zhao, Y. (2013) Climate-related changes in peatland carbon accumulation during the last millennium. *Biogeosciences*, 10, 929–944.
- Clarke P.J., Knox, K.J.E. & Butler, D. (2010) Fire intensity, serotiny and seed release in 19 woody species: evidence for risk spreading among wind-dispersed and resprouting syndromes. *Australian Journal of Botany*, 58, 629–636.
- Coaldrake, J.E. (1961) The ecosystem of the coastal lowlands (“wallum”) of southern Queensland. *Bulletin No. 283*, CSIRO, Melbourne. 138 pp.
- Couwenberg, J. and Joosten, H. (2005) Self-organization in raised bog patterning: The origin of microtope zonation and mesotope diversity. *Journal of Ecology*, 93, 1238–1248.
- Cox, M.E. James, A., Raiber, M., Taulis, M. & Hawke, A. (2011) North Stradbroke Island 3D hydrology: Groundwater systems overview. *Proceedings of the Royal Society of Queensland*, 117, 65–83.
- Da Silva, G.M. & Shulmeister, J. (2016) A review of coastal dunefield evolution in Southeastern Queensland. *Journal of Coastal Research*, 1, 308–312.
- DEHP (2013) *Regional Ecosystems*. Department of Environment and Heritage Protection, Brisbane. Online at: <http://www.ehp.qld.gov.au/ecosystems/biodiversity/regional-ecosystems/maps/index.php>, accessed 24 Jun 2013.
- DERM (2011) *Ecological Character Description Knowledge Gaps*. Queensland Wetlands Program project fact sheets, Department of Environment and Resource Management, Brisbane. Online at: <https://wetlandinfo.ehp.qld.gov.au/wetlands/resources/publications/fact-sheets/>, accessed 30 Jly 2018.
- Ellery, W.N., Ellery, K., McCarthy T.S., Cairncross, B. & Oelofse, R. (1989) A peat fire in the Okavango Delta, Botswana, and its importance as an ecosystem process. *African Journal of Ecology*, 27, 7–21.
- Emond, C., Lapointe, L., Hugron, S. & Rochefort, L. (2016) Reintroduction of salt marsh vegetation and phosphorus fertilisation improve plant colonisation on seawater-contaminated cutover bogs. *Mires and Peat*, 18(17), 1–17.
- Evans, P.A. (1995) *Cooloola Area Water Supply Investigation*. Water Resources Division, Queensland Department of Primary Industries, Brisbane, 32 pp.
- Farrell, C.A. & Doyle, G.J. (2003) Rehabilitation of industrial cutaway Atlantic blanket bog in County Mayo, North-West Ireland. *Wetlands Ecology and Management*, 11, 21–35.
- FIWHASAC (2004a) *Cooloola - Assessment of Potential Outstanding Universal Value*. Fraser Island World Heritage Area Scientific Advisory Committee, Queensland Environmental Protection Agency, Brisbane, 173 pp.
- FIWHASAC (2004b) *Fraser Island World Heritage Area - Review of Outstanding Universal Value*. Fraser Island World Heritage Area Scientific Advisory Committee, Queensland Environmental Protection Agency, Brisbane, 102 pp.
- Foster, D.R. & Fritz, S.C. (1987) Reviewed mire development, pool formation and landscape processes on patterned fens in Dalarna, Central Sweden. *Journal of Ecology*, 75, 409–437.
- Foster, D.R. & King, G.A. (1984) Landscape features, vegetation and developmental history of a patterned fen in south-eastern Labrador, Canada. *Journal of Ecology*, 72, 115–143.
- Foster, D.R., Wright, H.E. Jr., Thelaus M. & King, G.A. (1988) Bog development and landform dynamics in Central Sweden and South-Eastern Labrador, Canada. *Journal of Ecology*, 76, 1164–1185.
- Geoscience Australia (2009) Bathymetric and Topographic Dataset. Australian Ocean Data Network (AODN). Online at: <https://catalogue.aodn.org.au/geonetwork/srv/eng/main.home>, accessed 18 Jan 2019.
- Gallego-Sala, A.V., Charman, D.J., Brewer, S., Page,

- S.E., Prentice, I.C., Friedlingstein, P., Moreton, S. and 68 others (2018) Latitudinal limits to the predicted increase of the peatland carbon sink with warming. *Nature Climate Change*, 8, 907–913.
- Glaser, P.H., Wheeler, G.A., Gorham, E. & Wright, H.E.Jr. (1981) The patterned mires of the Red Lake peatland, northern Minnesota: vegetation, water chemistry and landforms. *Journal of Ecology*, 69, 575–599.
- Goode, D.A. & Lindsay, R.A. (1979) The peatland vegetation of Lewis. *Proceedings of the Royal Society of Edinburgh, Section B: Biological Sciences*, 77, 279–293.
- Gore, A.J.P. (ed.) (1983) *Mires: Swamp, Bog, Fen and Moor*. Ecosystems of the World 4B: Regional Studies, Elsevier, Amsterdam, 478 pp.
- Gorham, E. (1991) Northern peatlands: role in the carbon cycle and probable response to global warming. *Ecological Applications*, 1, 182–195.
- Griffith, S.J. & Wilson, R. (2007) Wallum on the Napiac Pleistocene barriers, lower North Coast of New South Wales. *Cunninghamia*, 10, 93–111.
- Griffith, S.J., Bale, C. & Adam, P. (2008) Environmental correlates of coastal heathland and allied vegetation. *Australian Journal of Botany*, 56, 512–526.
- Heinselman, M.L. (1965) String bogs and other patterned organic terrain near Seney, Upper Michigan. *Ecology*, 46, 185–188.
- Hilbert, D.W., Roulet, N. & Moore, T. (2000) Modelling and analysis of peatlands as dynamical systems. *Journal of Ecology*, 88, 230–242.
- Hobson, R.G. & Head, D.P. (1996) *A Survey of the Vertebrate Fauna of the Fens of Fraser Island and Rainbow Beach, South-east Queensland*. Queensland National Parks and Wildlife Service, Brisbane, 13 pp.
- Hodge, T.A. & Rapson, G.L. (2010) Is *Empodisma minus* the ecosystem engineer of the FBT (fen–bog transition zone) in New Zealand? *Journal of the Royal Society of New Zealand*, 40, 181–207.
- Hodgkinson, J., Cox, M.E. & McLoughlin, S. (2007) Groundwater mixing in a sand-island freshwater lens: Density-dependent flow and stratigraphic controls. *Australian Journal of Earth Sciences*, 54, 927–946.
- Hoekman, D.H. (2007) Satellite radar observation of tropical peat swamp forest as a tool for hydrological modelling and environmental protection. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 17, 265–275.
- Holden, J., Chapman, P.J. & Labadz, J.C. (2004) Artificial drainage of peatlands: hydrological and hydrochemical process and wetland restoration. *Progress in Physical Geography*, 28, 95–123.
- Hu, A. & Deser, C. (2013) Uncertainty in future regional sea level rise due to internal climate variability. *Geophysical Research Letters*, 40, 2768–2772.
- IUCN (2017) *IUCN Red List of Threatened Species, Version 3.1*. Online at: <http://www.iucnredlist.org/>, accessed 01 Nov 2017.
- Ivanov, K.E. (1981) *Water Movement in Mirelands*. English translation by A. Thompson and H.A.P. Ingram, Academic Press, London, 276 pp.
- Jackson, J.M. (2007) *Hydrogeology and Groundwater Flow Model, Central Catchment of Bribie Island, Southeast Queensland*. Thesis, Queensland University of Technology, Brisbane.
- Katic, P. & Quentin Grafton, R. (2011) Optimal groundwater extraction under uncertainty: Resilience versus economic payoffs. *Journal of Hydrology*, 406, 215–224.
- Krachler, R., Krachler, R., Valda, A., Keppler, B.K. (2019) Natural iron fertilization of the coastal ocean by “blackwater rivers”. *Science of the Total Environment*, 656, 952–958.
- Krull, E., Thompson, C.H. & Skjemstad, J.O. (2004) Chemistry, radiocarbon ages, and development of a subtropical acid peat in Queensland, Australia. *Australian Journal of Soil Research*, 42, 411–425.
- Larsen, G.R. & Cox, M.E. (2011) Hydrochemical and isotopic characterisation of groundwaters to define aquifer type and connectivity in a subtropical coastal setting, Fraser Coast, Queensland. *Environmental Earth Science*, 64, 1885–1909.
- Leach, L.M. & Gallagher, M. (2013) *North Stradbroke Island 2008 Transient Groundwater Flow Model*. Department of Science, Information Technology, Innovation and the Arts, Brisbane, 228 pp.
- Leifeld, J., Steffens, M. & Galego-Sala, A. (2012) Sensitivity of peatland carbon loss to organic matter quality. *Geophysical Research Letters*, 39, L14704, doi:10.1029/2012GL051856.
- Lewis, S.E., Sloss, C.R., Murray-Wallace, C.V., Woodroffe, C.D. & Smithers, S.G. (2013) Post-glacial sea-level changes around the Australian margin: A review. *Quaternary Science Reviews*, 74, 115–138.
- Lindsay, R.A. (1993) Peatland conservation — from cinders to Cinderella. *Biodiversity and Conservation*, 2, 528–540.
- Long, D.T., Fegan, N.E., Lyons, W.B., Hines, M.E., Macumber, P.G. & Giblin, A.M. (1992) Geochemistry of acid brines: Lake Tyrrell, Victoria, Australia. *Chemical Geology*, 96, 33–52.
- Mark, A.F., Johnson, P.N., Dickinson, K.J.M. & McGlone, M.S. (1995) Southern hemisphere

- patterned mires, with emphasis on southern New Zealand. *Journal of the Royal Society of New Zealand*, 25, 23–54.
- McDougall, A., Marshall, S. & Espinoza, T. (2017) Determining groundwater dependence of the Cooloola Patterned Fens in south-eastern Queensland, and threats posed by groundwater extraction. *Marine and Freshwater Research*, 68, 2336–2343.
- McFarland, D. (1988a) Fire and the vegetation composition and structure of subtropical heathlands in South-eastern Queensland. *Australian Journal of Botany*, 36, 533–546.
- McFarland, D. (1988b) The composition, microhabitat use and response to fire of the avifauna of subtropical heathlands in Cooloola National Park, Queensland. *Emu*, 88, 249–257.
- Moss, P., Shapland, F., Tibby, J., Barr, C. & Petherick, L. (2012) Fires in the fens: fire history and management of the patterned fens of south-east Queensland. In: *Ecology: Fundamental Science of the Biosphere*, ESA 2012 Annual Conference Handbook, Ecological Society of Australia, Melbourne, 197. Online at: <https://www.ecolsoc.org.au/files/conferences/2012-esa/conference-handbook-2012.pdf>, accessed 29 July 2019.
- Moss, P.T., Tibby, J., Petherick, L., McGowan, H. & Barr, C. (2013) Late Quaternary vegetation history of North Stradbroke Island, Queensland, eastern Australia. *Quaternary Science Reviews*, 74, 257–272.
- Moss, P., Tibby, J., Shapland, F., Fairfax, R., Stewart, P., Barr, C., Petherick, L., Gontz, A. & Sloss, C. (2016) Patterned fen formation and development from the Great Sandy Region, south-east Queensland, Australia. *Marine and Freshwater Research*, 67, 816–827.
- Newnham, R.M., de Lange, P.J. & Lowe, D.J. (1995) Holocene vegetation, climate and history of a raised bog complex, northern New Zealand based on palynology, plant macrofossils and tephrochronology. *The Holocene*, 5, 267–272.
- N.L.R. (1939) A Naturalist's Notebook: A rare parrot. *Maryborough Chronicle, Wide Bay and Burnett Advertiser*, Thu 7 Sep 1939 p.3. Online at: <https://trove.nla.gov.au/newspaper/article/151173879>, accessed 29 July 2019.
- NPRSR (2018) *Parks and Forests*. Department of National Parks, Sport and Racing, Queensland Government, Brisbane. Online at: <http://www.nprsr.qld.gov.au/parks/>, accessed 31 July 2018.
- Page, T.J., Sharma, S. & Hughes, J.M. (2004) Deep phylogenetic structuring has conservation implications for ornate rainbow fish (Melanotaeniidae: *Rhadinocentrus ornatus*) in Queensland, eastern Australia. *Marine and Freshwater Research*, 55, 165–172.
- Pakalne, M. & Aleksāns, O. (2017) Latvia. In: Joosten, H., Tanneberger F. & Moen, A. (eds.) *Mires and Peatlands of Europe: Status, Distribution and Conservation*. Schweitzerbart Science Publishers, Stuttgart, 478–485.
- Parish, F., Sirin, A., Charman, D., Joosten, H., Minayeva, T., Silvius, M. & Stringer, L. (eds.) (2008) *Assessment on Peatlands, Biodiversity and Climate Change: Main Report*. Global Environment Centre, Kuala Lumpur and Wetlands International, Wageningen, 206 pp.
- Petherick, L., McGowan, H. & Moss, P. (2008) Climate variability during the Last Glacial Maximum in eastern Australia: Evidence of two stadials? *Journal of Quaternary Science*, 23, 787–802.
- Pitkänen, A., Turunen, J. & Tolonen, K. (1999) The role of fire in the carbon dynamics of a mire, eastern Finland. *The Holocene*, 9, 453–462.
- Posa, M.R.C., Wijedasa, L.S. & Corlett, R.T. (2011) Biodiversity and conservation of tropical peat swamp forests. *BioScience*, 61, 49–57.
- Queensland Government (2018) *Groundwater Database, Queensland*. Queensland Government, Brisbane. Online at: <https://data.qld.gov.au/dataset/groundwater-database-queensland>, accessed 29 July 2018.
- Queensland Herbarium (2019) *Regional Ecosystem Description Database (REDD)*. Version 10.1 (March 2018). Queensland Department of Environment and Science, Brisbane. Online at: <https://www.qld.gov.au/environment/plants-animals/plants/ecosystems/descriptions/download>, accessed 04 Aug 2019.
- Queensland Treasury (2011) *Queensland Government Population Projections to 2031: Local Government Areas*. 2011 edition, Office of Economic and Statistical Research, Queensland Treasury, Brisbane, 67 pp. Online at: <http://www.qgso.qld.gov.au/products/reports/qld-govt-pop-proj-lga/index.php>, accessed 29 July 2019.
- Reeve, R. & Fergus, I.F. (1982) Black and white waters and their possible relationship to the podzolization process *Australian Journal of Soil Research*, 21, 59–66.
- Rennermalm, A.K., Nordbotten, J.M. & Wood, E.F. (2010) Hydrologic variability and its influence on long-term peat dynamics. *Water Resources Research*, 46(12), W12546.
- Rydin, H. & Jeglum, J.K. (2006) *The Biology of Peatlands*. Oxford University Press, UK, 382 pp.

- Sadat-Noori, M., Santos, I.R., Tait, D.R., McMahon, A., Kadel, S. & Maher, D.T. (2016) Intermittently Closed and Open Lakes and/or Lagoons (ICOLLs) as groundwater-dominated coastal systems: Evidence from seasonal radon observations. *Journal of Hydrology*, 535, 612–624.
- Seymour, J. (1981) The Cooloola sanddunes. *ECOS*, 30, 3–11. Online at: http://www.ecosmagazine.com/?act=view_file&file_id=EC30p3.pdf, accessed 28 Jly 2019.
- Shapland, F., Moss, P., Petherick, L., Tibby, J. & Barr, C. (2012) Paleoenvironmental reconstruction over the late Quaternary period for patterned fens at Moon Point, Fraser Island. In: *Ecology: Fundamental Science of the Biosphere*, ESA 2012 Annual Conference Handbook, Ecological Society of Australia, Melbourne, 197. Online at: <https://www.ecolosc.org.au/files/conferences/2012-esa/conference-handbook-2012.pdf>, accessed 29 Jly 2019.
- Silva, A.C.F., Tavares, P., Shapouri, M., Stigter, T.Y., Monteiro, J.P., Machadom M., Cancela da Fonseca, L. & Ribeiro, L. (2012) Estuarine biodiversity as an indicator of groundwater discharge. *Estuarine, Coastal and Shelf Science*, 97, 38–43.
- Sinclair, J. & Corris, P. (1994) *Fighting for Fraser Island*. Kerr Publishing Pty Ltd., Alexandria, New South Wales, Australia, 204 pp.
- Spring, K. (2005) *Groundwater Flow Model for a Large Sand Mass with Heterogeneous Media, Bribie Island, Southeast Queensland*. Masters Thesis, Queensland University of Technology, Brisbane, Australia, 187 pp. Online at: https://eprints.qut.edu.au/16230/1/Ken_Spring_Thesis.pdf, accessed 29 Jly 2019.
- Srivastava, S.K., King, L., Mitchell, C., Wiegand, A., Carter, R.W., Shapcott, A. & Russell-Smith, J. (2013) Ecological implications of standard fire-mapping approaches for fire management of the World Heritage Area, Fraser Island, Australia. *International Journal of Wildland Fire*, 22, 381–393.
- State of Queensland (2017) *Water Monitoring Information Portal*. Queensland Government, Brisbane. Online at: <https://water-monitoring.information.qld.gov.au/>, accessed 08 Jan 2019.
- Steiner, G.M. (ed.) (2005) *Moore – von Siberien bis Feuerland (Mires – from Siberia to Tierra del Fuego)*. Stapfia 85, Biologiezentrum der Oberösterreichischen Landesmuseen, Linz, Austria, 626 pp. (in German and English).
- Stockwell, B., Hutchison, M., Wedlock, B., Ford, E., Anderson, T., Thompson, C. & Stephens, K. (2004) *Freshwater Aquatic Biodiversity in the Burnett Mary Region. Peer Review Version Technical Paper*. Report prepared for the Burnett Mary Regional Natural Resource Management Group, Bundaberg, Australia, 47 pp.
- Strack, M. (ed.) (2008) *Peatlands and Climate Change*. International Peat Society, Jyväskylä, Finland, 223 pp.
- Surawski, N., Tularam, A. & Braddock, R. (2005) Sustainability of groundwater extraction for the Pimpama coastal-plain, Queensland, Australia. In: Zerger, A. & Argent, R.M. (eds.) *MODSIM 2005: International Congress on Modelling and Simulation*, Modelling and Simulation Society of Australia and New Zealand, 2366–2372.
- Sweett, C. (2008) *Lines in the Sand. A History of Mineral Sandmining on Queensland's Barrier Islands*. History Thesis, University of Queensland, Brisbane, 96 pp.
- Taffs, K.H., Parr, J.F. & Bolton, K.G. (2006) Using palaeobotanical techniques to guide peatland restoration. A case study from Byron Bay, Australia. *Ecological Management and Restoration*, 7, 133–135.
- Thompson, C.H. (1992) Genesis of podzols on coastal dunes in southern Queensland .I. Field relationships and profile morphology. *Australian Journal of Soil Research*, 30, 593–613.
- Thompson, C.H. (2004) Fraser Island and other coastal sand masses of southern Queensland: Some geomorphic, pedological, hydrological and ecological perspectives. Appendix 1 of *Fraser Island World Heritage Area Review of Outstanding Universal Value*, Fraser Island World Heritage Area Scientific Advisory Committee, Queensland Environmental Protection Agency, Brisbane, 102 pp.
- Turetsky, M., Wieder, K., Halsey, L. & Vitt, D. (2002) Current disturbance and the diminishing peatland carbon sink. *Geophysical Research Letters*, 29(11), 1526, 21-1–21-4.
- Twyford, K. (1996) Fraser's newly discovered fens. *MOONBI*, 89, 11 pp. (Newsletter of the Fraser Island Defenders Organisation (FIDO), Milton, Queensland).
- UNESCO/WHC (2018) *Great Sandy World Heritage Area*. Tentative Lists, UNESCO World Heritage Centre. Online at: <http://whc.unesco.org/en/tentativelists/5480>, accessed 26 July 2018.
- van Dam, H. & Beltman, B. (1992) Effects of climatic change on chemistry and vegetation of peatlands, with special reference to interaction with atmospheric deposition. *Wetlands Ecology and Management*, 2, 63–68.
- Vasander, H., Tuittila, E.-S., Lode, E., Lundin, L., Ilomets, M., Sallantausta, T., Heikkilä, R.,

- Pitkänen, M.-L. & Laine, J. (2003) Status and restoration of peatlands in northern Europe. *Wetlands Ecology and Management*, 11, 51–63.
- Viswanathan, N.N. (1990) Mineral sand mining and its effect on groundwater quality. *Water Science and Technology*, 22, 95–100.
- von Stieglitz, C.R., McDonald, A. & Wentholt, L.R. (1963) Experiments in utilization of Wallum country in south-eastern Queensland. *Queensland Journal of Agricultural Science*, 20, 299–321.
- Ward, W.T. (2006) Coastal dunes and strandplains in southeast Queensland: sequence and chronology. *Australian Journal of Earth Sciences*, 53, 363–373.
- Watson, P. (2001) *The Role and Use of Fire for Biodiversity Conservation in South-east Queensland: Fire Management Guidelines Derived from Ecological Research*. SEQ Fire and Biodiversity Consortium, Brisbane, 49 pp. Online at: <http://www.gloriousnebo.org.au/LOR/FireUse.pdf>, accessed 29 Jly 2019.
- Westman, W.E. (1975) Pattern and diversity in swamp and dune vegetation, North Stradbroke Island. *Australian Journal of Botany*, 23, 339–354.
- Wetlands International (1999) *Information Sheet on Ramsar Wetlands*. Online at: ramsarsites.wetlands.org/reports/ris/5AU050en.pdf, accessed 23 Jun 2013.
- Whinam, J., Hope, G.S., Clarkson, B.R., Buxton, R.P., Alspach, P.A. & Adam, P. (2003) *Sphagnum* in peatlands of Australasia: Their distribution, utilisation and management. *Wetlands Ecology and Management*, 11, 37–49.
- White, M. & Payette, S. (2016) Pool size structure indicates developmental stages of boreal fens. *Botany*, 94, 643–651.
- Whittington, P.N. & Price, J.S. (2006) The effects of water table draw-down (as a surrogate for climate change) on the hydrology of a fen peatland, Canada. *Hydrological Processes*, 20, 3589–3600.
- Williams, K.J. & Crimp, S. (2012) *Queensland's Biodiversity Under Climate Change: an Overview of Climate Change in Queensland*. CSIRO Climate Adaptation Flagship Working Paper No. 12A, Commonwealth Science and Industrial Research Organisation (CSIRO), Canberra, 34 pp. Online at: https://research.csiro.au/climate/wp-content/uploads/sites/54/2016/03/12A_CAF-Working-Paper-12A.pdf, accessed 29 Jly 2019.
- Winkler, M.G. & Dewitt, C.B. (1985) Environmental impacts of peat mining in the United States. *Environmental Conservation*, 12, 317–330.
- Wołejko, L., Grootjans, A.P., Pakalne, M., Strazdina, L., Aleksāns, O., Elskehawi, S. & Grabowska, E. (2019) The biocenotic value of Slītere National Park, Latvia, with special reference to inter-dune mires. *Mires and Peat*, 24(13), 1–18.
- Yu, Z., Loisel, J., Brosseau, D.P., Beilman, D.W. & Hunt, S.J. (2010) Global peatland dynamics since the Last Glacial Maximum. *Geophysical Research Letters*, 37, L13402, 1–5.
- Yurkovskaya, T. (2005) Distribution of mire types in Russia. In: Steiner, G.M. (ed.) *Moore – von Siberien bis Feuerland (Mires – from Siberia to Tierra del Fuego)*, Stapfia 85, Biologiezentrum der Oberösterreichischen Landesmuseen, Linz, Austria, 261–274.
- Zhang, H., Gallego-Sala, A.V., Amesbury, M.J., Charman, D.J., Piilo, S.R. & Väiliranta, M.M. (2018) Inconsistent response of arctic permafrost peatland carbon accumulation to warm climate phases. *Global Biogeochemical Cycles*, 32(10), 1605–1620.
- Zoltai, S.C., Morrissey, L.A., Livingston, G.P. & de Groot, W.J. (1998) Effects of fires on carbon cycling in North American boreal peatlands. *Environmental Reviews*, 6, 13–24.

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