Hydrological Sciences Journal
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/thsj20

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Version of record first published: 16 Dec 2011.

To cite this article: M. C. Acreman , R. J. Harding , C. Lloyd , N. P. McNamara , J. O. Mountford , D. J. Mould , B. V. Purse , M. S. Heard , C. J. Stratford & S. J. Dury (2011): Trade-off in ecosystem services of the Somerset Levels and Moors wetlands, Hydrological Sciences Journal, 56:8, 1543-1565

To link to this article: http://dx.doi.org/10.1080/02626667.2011.629783

Trade-off in ecosystem services of the Somerset Levels and Moors wetlands

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Received 5 July 2010; accepted 6 January 2011; open for discussion until 1 June 2012

Editor Z.W. Kundzewicz

Citation Acreman, M.C., Harding, R.J., Lloyd, C., McNamara, N.P., Mountford, J.O., Mould, D.J., Purse, B. V., Heard, M.S., Stratford, C.J. and Dury, S.J., 2011. Trade-off in ecosystem services of the Somerset Levels and Moors wetlands. *Hydrological Sciences Journal*, 56 (8), 1543–1565.

Abstract It is widely recognized that healthy ecosystems can provide considerable benefits to people, including food, timber, freshwater, protection from floods and much of what we call quality of life. A global review of these ecosystem services carried out as part of the Millennium Ecosystem Assessment (MEA) provided a framework for national and local studies. Using the MEA approach, this paper reviews the ecosystem services provided by the Somerset Levels and Moors wetland system in southwest England. This wetland provides a series of important services that are beneficial locally, regionally and globally, including grazing for cattle, carbon sequestration, flood water storage, recreation and archaeology. Some services are synergistic and reinforcing; for example, maintaining wet conditions supports wetland bird life that maintains biological diversity, attracts tourists, protects archaeological artefacts and reduces CO_2 emissions; raising water levels to or above the ground leads to net greenhouse gas uptake by the wetland. Other services are potentially conflicting, for example raising water levels may reduce potential flood water storage and increase methane emissions. Comparison of the services of the wetland with those of drier habitats reveals for example that carbon sequestration, bird habitat provision and hay production is greater in wetlands, whilst grazing quality may decline and plant diversity may be reduced in the short term and distributions of disease vectors may be altered by wetland restoration through raising water levels. Management decisions affecting wetlands may necessitate a trade-off of ecosystem services.

Key words ecosystem services; wetlands; Somerset Levels and Moors; ecosystem function; floods; water resources; carbon sequestration; tourism; archaeology

Compromis entre les services écosystémiques des zones humides “Somerset Levels and Moors”

Résumé Il est largement reconnu que des écosystèmes sains peuvent fournir des avantages considérables aux personnes, comprenant de la nourriture, du bois, de l’eau douce, la protection contre les inondations et une grande partie de ce que nous appelons la qualité de vie. Un examen global de ces services écosystémiques, réalisées dans le cadre du Millennium Ecosystem Assessment (MEA), a fourni un cadre pour des études nationales et locales. En utilisant l’approche MEA, le présent article passe en revue les services écosystémiques fournis par les zones humides “Somerset Levels and Moors” situées dans le sud de l’Angleterre. Ces zones humides fournissent une série de services importants qui sont bénéfiques au niveau local, régional et mondial, comprenant le pâturage pour le bétail, la séquestration du carbone, le stockage des eaux de crue, les loisirs et l’archéologie. Certains services sont en synergie et, par exemple, le maintien des conditions humides favorise la vie des oiseaux des milieux humides et maintient la diversité biologique, attire les touristes, protège des objets archéologiques et réduit les émissions de CO_2; élever les niveaux de l’eau au niveau ou au-dessus du sol conduit à l’absorption nette de gaz à effet de serre par les milieux humides. D’autres services sont potentiellement conflictuels, par exemple l’augmentation du niveau d’eau peut réduire le potentiel de stockage des eaux de crue et augmenter les émissions de méthane. La comparaison des services des zones humides avec ceux d’habitats plus secs révèle, par exemple, que la séquestration du carbone, la fourniture d’habitats aux oiseaux et la production de foin sont plus importantes dans les zones humides, tandis que la qualité des pâturages peut diminuer, que la diversité des plantes peut être

ISSN 0262-6667 print/ISSN 2150-3435 online

http://dx.doi.org/10.1080/02626667.2011.629783
http://www.tandfonline.com

réduite à court terme et que la distribution des vecteurs de maladies peut être modifié par la restauration des milieux humides grâce à l'élévation des niveaux d'eau. Les décisions de gestion affectant les zones humides peuvent nécessiter un compromis entre les services écosystémiques.

Mots clefs services écosystémiques; zones humides; Somerset Levels and Moors; fonction de l'écosystème; inondations; ressources en eau; séquestration du carbone; tourisme, archéologie

INTRODUCTION

The general perception of wetlands has changed dramatically over the past 30 years. Formerly treated as wastelands (Maltby 1986), wetlands have been considered more recently as "biological supermarkets", because of goods and products they provide (such as fish and grazing land), and "the kidneys of the landscape" because of the services they perform, such as flood management and water quality improvement (Mitsch and Gosselink 1993). The benefits of wetlands to human society were recognized in studies collated in the USA in the 1980s (Adamus and Stockwell 1983, Bardecki 1984, Carter 1986). The ecosystem services of wetlands were defined and promoted by organizations, such as IUCN—The International Union for the Conservation of Nature (Dugan 1990), Wetlands International (Davis and Claridge 1993) and the Ramsar Convention on Wetlands of International Importance (Davis 1993). They have influenced international wetland policy (OECD 1996) and its uptake at national (e.g. Zimbabwe and Uganda) and continental levels, e.g. in Europe (CEC 1995) and in Asia (Howe *et al.* 1992). The economic importance of wetlands has been further demonstrated through economic valuation of these services (e.g. Costanza *et al*. 1997, Barbier *et al.* 1997, Wilson *et al*. 1999, Emerton 2005, Turner *et al*. 2009, Kuik *et al*. 2009). Indicators have been developed to value the ecosystem services of, for example, lowland floodplains (Posthumus *et al*. 2010). In the UK, it has been estimated that upland and lowland management to restore floodplains and improve water quality has benefit–cost ratios of up to 4:1 (Natural England 2009).

Wetlands are naturally dynamic and transient features of the landscape. In the short term, the dynamic nature of the hydrological regimes of wetlands leads to continuous change in habitat availability. For example, during wet periods, high water levels can create habitats, e.g. backwaters, sidearm channels, oxbow lakes and temporary pools on floodplains, which subsequently disappear. In the longer term, many wetlands naturally infill with sediment and vegetation and become gradually drier as they are colonized by floating and emergent plants and, successively, fringing and finally terrestrial plants. Conservation of many wetlands in a particular desired state thus frequently requires continual management to suppress natural changes. For example, the wet grasslands of the Nene Washes in Cambridgeshire, UK have been created and maintained by grazing by horses and cattle (Benstead *et al.* 1997) where the sucessional natural vegetation would be forest. Furthermore, some wetlands have been created by human action e.g. Rutland Water is an artificial water supply reservoir in the UK that has been designated under the Ramsar Convention as a wetland of international importance. Wetland formation and development has also been influenced by climate, and some wetlands formed in wetter and cooler past climates and may no longer be stable under current or possible future hydrological conditions. For example, future climate change is likely to have significant impacts on wetlands, with water stress likely in southern England during late summer and autumn (Acreman *et al*. 2009).

The Millennium Ecosystem Assessment (MEA 2005) involved a comprehensive review of available evidence to appraise the global environment, focusing on ecosystem services and how changes in them have affected and will have impacts upon human well-being. The MEA report showed that human activities have changed most ecosystems and threaten the Earth's ability to support future generations. The concept of ecosystem services was used to aid understanding of the human use and management of natural resources (de Groot 1992). Ecosystem services are natural assets (Barbier 2009); they are the processes by which the natural environment produces resources utilized by humans, such as clean air, water, food and materials and contributes to social and cultural well-being (Fischer *et al.* 2009), and much of what we call quality of life (Acreman 2003). They can be defined in various ways, but the MEA classified ecosystems services and their links to human well-being as follows (Fig. 1):

(a) *Supporting services*: Services necessary for the production of all other ecosystem services including soil formation, photosynthesis, primary production and nutrient cycling;

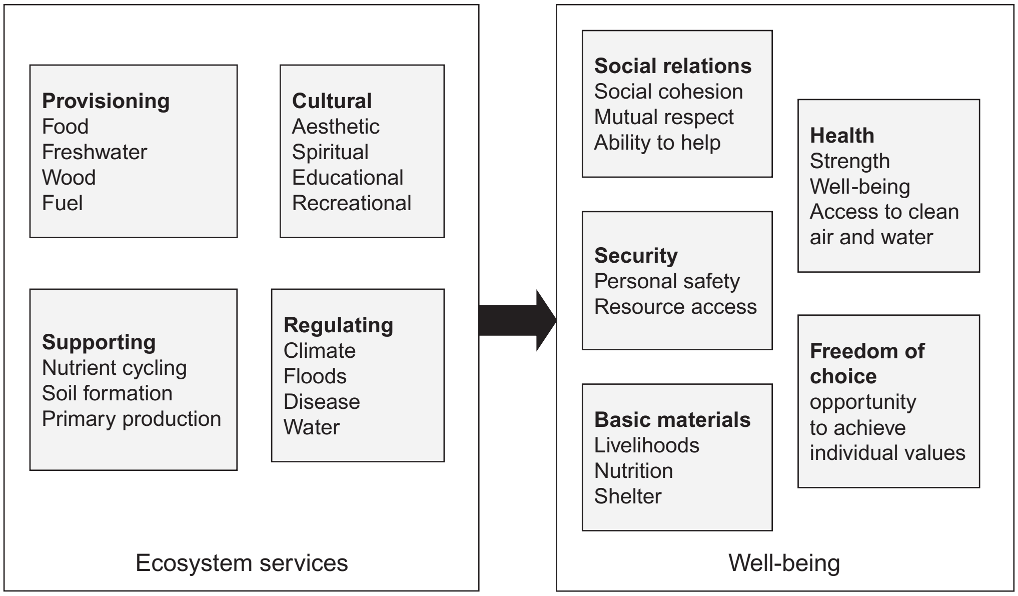

Fig. 1 Ecosystem services and human well-being (after MEA 2005).

(b) *Provisioning services*: Products obtained from ecosystems, including food, fibre, fuel, genetic resources, natural medicines, pharmaceuticals and fresh water;

(c) *Regulating services*: Benefits obtained from the regulation of ecosystem processes, including air quality, climate, water, erosion, disease, pests and hazard, such as floods; and

(d) *Cultural services*: Non-material benefits obtained from ecosystems through spiritual enrichment, cognitive development, reflection, recreation and aesthetic experiences, including landscape value.

The MEA framework was used by EFTEC *et al*. (2006) to conclude that carbon budget management, water quality and flood risk management were amongst the most important of England's ecosystem services. This paper uses the MEA framework to review the ecosystem services of the Somerset Levels and Moors (SLM) wetland, UK. It describes the services individually and then identifies interrelationships between the services to assess whether these are linked, reinforcing or conflicting. It then examines the implications of different management options to achieve a sustainable future for the SLM (under changing climate). The paper addresses many of the limitations in previous ecosystem services research, including the past focus on single services and a lack of analysis of feedbacks and interactions between ecological and social systems (Nicholson *et al*. 2009).

STUDY SITE

Peat-dominated soil wetlands have been recognized as providing particularly important ecosystem services (Maltby 1986). Perhaps the most important peat wetland in the UK is the Somerset Levels and Moors (SLM); covering 650 km^2 in southwest England (Taylor 1999) between the Quantock and Mendip hills (Fig. 2). These wetlands are classified broadly as fens receiving water and nutrients from the soil, rock and groundwater as well as from rainfall. The similar wetlands that occur on the north side of the Mendip Hills are normally distinguished from the SLM as the Avon and Gordano Levels (or North Somerset Levels). The wetlands form a distinctive landscape

Fig. 2 Location of the Somerset Levels and Moors in the UK.

mosaic with a complex set of economic, social and environmental interactions and potential aspirations (Maltby and Hogan 1992), including peat mining, intensive agriculture and recreation.

The topography is generally flat with over 200 islands of solid and drift geology, such as Brent Knoll, Burrow Mump and Glastonbury Tor and ridges, such as the Polden Hills, which rise above the Holocene valley floor deposits. The Moors lie between mean sea level and 10 m a.m.s.l. They were inundated in about 6000 BC when sea level rose after the last ice age, depositing marine clay (Campbell *et al*. 1998). Peat formation on top of the clay began around 4500 BC and continued in places until the end of early 19th century. The Levels are a sand, clay and peat bar about 6 m a.m.s.l., separating the Moors from the coast. The area is drained by three main river systems; the Brue, Axe and Parrett. The extensive wet floodplain pastures have been the scene of human activity since at least 4000 BC, with some of the most important water-logged archaeological remains in Europe from prehistoric through Roman to recent times.

Since Medieval times, efforts have been made to drain the land. Large artificial channels, such as the North Drain and King's Sedgemoor Drain and a series of pumping stations have been constructed and most of the river channels canalized to aid drainage, but areas are still prone to winter floods of fresh water and occasional salt water inundations. The resulting landscape is one of pastures, separated by ditches, lined by willow trees. Historical water management, peat extraction for fuel and horticulture and grazing have produced a unique landscape of wetland plant and animal communities.

To intensify agriculture during the 20th century and particularly after World War II, large pumping stations were built to lower water levels and allow access by machinery throughout the year. Pump drainage facilitated cultivation of peat for arable production, although intensification did not occur to the same extent in SLM as on other UK wetlands, such as the East Anglian Fens. Nevertheless, efforts to increase agricultural productivity mainly during the 1970s and 1980s progressively reduced wetness by generally lowering water levels in the winter and reducing flooding (Williams 1970). In the summer, water levels were raised to provide drinking water for stock and so that the ditches acted as wet fences between fields. The resulting water level regime for the North drain is labelled as "pumped" in Fig. 3, which is too dry in winter for water birds and too wet in summer for flood-meadow plant communities. This is a typical water level regime for much of the SLM. Lower water levels and arable production also accelerated peat wastage (Brown 2009).

During the 1980s, the Environmentally Sensitive Areas Scheme (ESA; http://www.naturalengland.org.uk) was introduced to provide incentives to encourage agricultural practices that would safeguard and enhance areas of particularly high landscape, wildlife or historic value. Under ESA, land owners were encouraged to operate a more natural water level regime, for which they could receive annual subsidies of up to £700 per hectare. There were several options for raised water levels, for example Tier 3 had a target of maintaining ditch water at mean field level during the winter and 300 mm below this level during the summer. A typical example of the Tier 3 water level regime is shown in Fig. 3 for Tadham Moor. Tier 3 seasonal water regime provides a cycle of multiple ecosystem services, including peat conservation, wildlife habitat for over-wintering birds, diverse wet grassland plant communities, traditional summer grazing and hay making (Morris *et al.* 2008). As an example, some 160 ha of the North Drain catchment (that contains Tadham Moor) have Tier 3 water levels, out of a total area of 4023 ha (UBLBDB 2010); the maximum potential extent of Tier 3 is around 2500 ha.

The juxtaposition of two objectives of maintaining a highly-valued working and productive landscape and achieving high conservation status have produced a wetland of international importance, rich heritage and unique landscape environment and culture. It remains the largest coastal and floodplain grazing marsh in England and some 35 000 ha have been designated as a Ramsar site under the International Convention on Wetlands (http://www.ramsar.org), particularly for the large populations of wintering and breeding waterbirds that it supports. National nature reserves within the SLM also conserve important floristic communities and invertebrate species. The area is a candidate for a World Heritage Site (http://www.whc.unesco.org) for its cultural heritage and landscape features.

ECOSYSTEM SERVICES

In this section each of the ecosystem services is described according to the MEA framework.

Provisioning services

Food The primary means of human food production on the SLM is the grazing of dairy and beef cattle, though arable farming is important locally on better-drained land. Until the 19th century, the SLM were used principally for summer grazing, due to extensive winter flooding. Indeed, the name Somerset (derived from old English *Sumorsaete*) means *land of the summer people*. The milk from the cattle has been used for cheese making at Cheddar since at least 1086 when it was listed in the Domesday Book. Financial records from King Henry II's Exchequer from 1170 include the purchase of 10 420 lb at a farthing per pound (£3 per ton) using 10 litres of milk to make 1 kg. The cheese was originally matured in the caves in Cheddar Gorge and has always been a valuable product. At that time, Cheddar cheese had to be made within 30 miles (48 km) of Wells Cathedral, but is now produced globally, such that a unique ecosystem service has been replicated elsewhere.

The nutritional value of wetland grasses for livestock was examined in a replicated block experiment set up in 1994 at Tadham Moor. This work tested the impact of Tier 3 raised water-levels (Fig. 3) on biodiversity and agriculture, thus facilitating a comparison of ecosystem services between wet and drier lands (Mountford *et al*. 1999). In the experiment, water levels were raised (Tier 3) in three blocks of fields and compared with unaltered (pumped) dry control blocks. Tier 3 water levels imposed a production penalty compared with non-raised conditions. Reductions in both hay yield (approx. 10%) and liveweight production from the hay re-growth (>40%) were found under raised water levels. However, these wetter conditions appeared to provide greater predictability in hay production compared with non-raised meadows. Previously fertilised grass-dominant plots showed both a greater negative response to raised water levels when they were first established, and then greater variation between years under than unfertilized meadows (Tallowin 1997).

The digestibility by livestock of the dry matter obtained under raised water level areas was similar to values obtained under drier pre-raised conditions, but nevertheless 15–20% lower than might be expected for conserved forages from agriculturally improved grass. The nitrogen content of the herbage cut for hay was sub-optimal for productive ruminant livestock. During the earlier years of the wetland restoration experiment the herbage potassium and phosphorus (P) contents were sub-optimal but by the end were close to adequacy for productive livestock. Calcium (Ca), magnesium and sodium contents in the dry matter were adequate for productive livestock. The Ca:P ratios of the dry matter produced under raised water levels were consistently supra-optimal for livestock, which could lead to trace element deficiency, if the hay was used as the principal winter feed without supplementation (Mountford and Cooke 2003).

Freshwater The SLM is characterized by abundant water availability for most of the year, due to a combination of its location near the outlet of a river basin, low lying topography, permeable peat soils and good rainfall (1325 mm per year). This makes the SLM attractive for water supply provision. During the Second World War, a munitions facility, the Royal Ordnance Factory, was constructed at Puriton. Production required a guaranteed all year-round clean water supply of 20×10^6 L per day. A 8-km-long, 200-m-wide reservoir was excavated called the River Huntspill, due to its canal-line form,

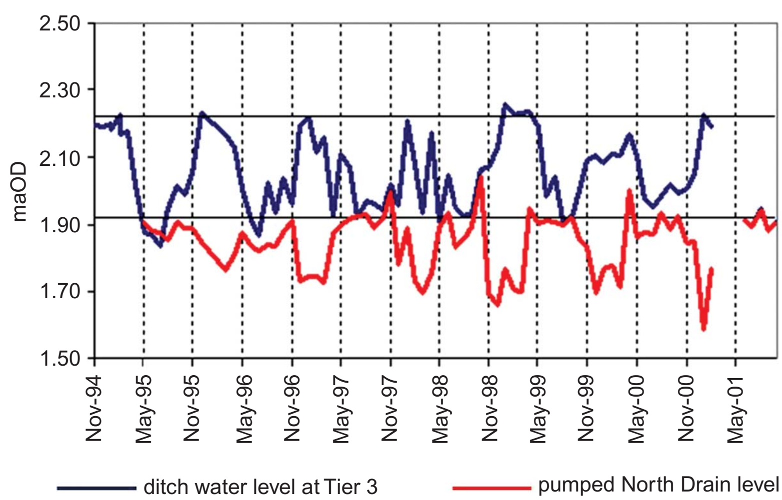

Fig. 3 Monthly ditch water level under Tier 3 and monthly pumped drainage level (North Drain).

with water retained by sluices at both ends. At the inland end of the river a pumping station, at Gold Corner, maintains water levels in the summer by pumping from the moors. During the winter, the Huntspill acts as a store for floodwater that can drain by gravity to the sea.

The availability of freshwater for human use is dictated by the balance between water inputs (from precipitation and streamflow) and outputs (outflow to the sea and evaporation); there is little groundwater as the wetlands are underlain by impermeable marine clays. Wetlands are generally considered to have higher evaporation rates than many other land types (Bullock and Acreman 2003, Peacock and Hess 2004). Measurements of evaporation were made from July to November 1999 on two wetland types—wet grassland at Tadham Moor and reedbeds at Ham Wall (Acreman *et al.* 2003a). The evaporation from the reed bed exceeded that of the wet grassland by 14% (or 50 mm over the 5 months) and the evaporation rates at both wetland sites exceeded the reference evaporation for short non-wetland grass (Penman 1948). At the grassland site, it was shown that evaporation increased with higher ditch water levels (Acreman *et al.* 2003a). It is thus clear that replacing dry grassland by wet grasslands and reedbeds can increase evaporation and thus reduce overall water resources availability downstream.

Peat Peat accumulation in the northern hemisphere was triggered largely by postglacial warming that opened up the depressions and lake-rich landscapes that in-filled subsequently with organic detritus (Maltby 2008). In the UK, peat covers around 1.65×10^6 ha (Lindsay and Immirzi 1996), or about 7% of the land area, but losses are between 2.8 and 5.8×10^6 t of CO_2 per year from the cultivation and drainage of lowland peat soils (Thompson 2008). Based on the shadow price of carbon (£26.5 per tonne of CO_2 equivalent), the annual value of this loss is estimated at £74 million–£150 million.

Peat has been used as fuel in and around the SLM since at least Roman times, having a calorific value of around 20 MJ kg^{-1} (Ekono 1981), which is similar to wood and lignite. Production of peat for fuel peaked in the 18th and 19th centuries and then declined with the advent of electric power. Peat is also a very productive plant growing medium and a basic component of standard "John Innes^{TM}" blends (Bunt 1988). During the 20th century, peat extraction was primarily for horticultural use, with UK production of 170 000 tons in 1980 (Williams and Williams 1992). Brown (2009) estimated that the total carbon storage of the SLM is approximately 10.9×10^6 t and that carbon in the upper 1 m of the soil profile, the most vulnerable to wastage by wind erosion, amounts to 3.3×10^6 t. Current (2010) retail prices of peat for horticultural compost are £7.50 for 60 litres.

During the 1960s, major commercial companies introduced intensive methods of extraction replacing shallow hand sod cutting with deep trenches. Although such peat harvesting is exploiting a provisioning ecosystem service, intensive extraction is a short-term benefit and may be unsustainable as it rapidly destroys the natural ecosystem and may not recover as peat is unlikely to re-accumulate under current and probable future climatic conditions. During the 1980s and 1990s, campaigns were launched to save the surviving peatlands (e.g. Friends of the Earth 1990). Despite pressure to conserve remaining peat stocks, new extractions licences were granted, though this has recently ceased. At present, around 1450 t of carbon is being removed annually by peat extraction, presenting 0.01% of the total stored. This is less than 10% of the 20 000 t soil wastage (erosion and oxidation). The combined loss of carbon from peat extraction and peat wastage is estimated at 21 450 t per annum, or 0.2% of the total store (Brown 2009). The UK Biodiversity Action Plan (http://www.ukbap.org.uk) contains targets for the replacement of peat in the UK horticultural industry, including supplies for amateur use; a reduction of 90% by 2010 (Alexander *et al.* 2008). Furthermore, ownership of many of the former peat working was transferred to nature conservation organizations, such as Natural England and the Royal Society for the Protection of Birds (RSPB) (Robertson 1993).

Baskets and other willow products Willow (*Salix* spp.) has been used for many centuries on the SLM as a construction material, particularly for basket making (Coles 1990), and was employed to build causeways across the Moors in the Iron Age. Willow is harvested by coppicing, in which trees are cut back to the main trunk. New shoots of willow, called "withies", grow out of the trunk and are cut periodically for use; the resulting "lollypop" form gives the wetland landscape a particular characteristic, which appears frequently in art. During the 1930s over 36 km^2 of willow were being grown commercially. Following the replacement of baskets with plastic bags and cardboard boxes, the industry has declined severely since the 1950s. By 2000, only around 1.4 km^2 were grown commercially; the SLM is now the only area in the UK where basket willow is grown commercially. The main species for weaving is *Salix triandra* (Almond Willow, *Black Maul*), while *Salix viminalis* (Common Osier) is used for handles, furniture and hurdles. Products including baskets, eel traps, lobster pots and furniture, were widely made from willow throughout the area in the recent past. The willow industry remains a source of employment, with around 100 people making their living from it. The Willows and Wetlands Visitor Centre maintains traditional methods and offers tours of over 32 ha of withies, willow yards and basket workshops, and explains the place of willow in the history of the SLM. Today, willow is used to make hurdles (for horse racing and fencing), artist's charcoal, baskets, furniture, cricket bats, and hot air balloon baskets, and for sculptures, such as the 12m high *Willow Man* (by Serena de la Hey), next to the M5 motorway near Pawlett.

Regulating services

Microclimate The enhanced evaporation over a wetland surface, compared to a drier terrestrial surface, can moisten and cool the lower atmosphere and lead to a reduction in evaporation (Oke 1997). This "oasis effect" is well known in arid climate (Polcher *et al*. 2008). There is also the possibility for a changed cloud cover over a wetland, linked to the modified evaporation and surface energy fluxes and modified rainfall as occurs in the inner Niger delta, Mali (Taylor 2009). The magnitude of these influences depends on the size of the wetland, the contrast with the surrounding region and the overlying weather patterns. An area the size of the Somerset levels might exhibit increased cloudiness and thunderstorm activity in the summer months, but there are no observational studies showing this. During 1999, the Centre for Ecology and Hydrology, UK ran a weather station at Tadham Moor on the levels (see Acreman *et al.* 2003a). A comparison with Yeovilton air-station (25 km to the southwest and outside the wetland) shows the air over Tadham Moor had a higher daytime humidity and a slightly lower temperature leading to a substantially lower vapour pressure deficit in the day (Fig. 4). The vapour pressure deficit is one of the primary drivers of evaporation and we would infer that the potential evaporation over the wetland would be 10–20% lower, demonstrating a strong feedback. Actual evaporation from Tadham would almost certainly be higher than from Yeovilton because of the freely available and continuous surface water. The lower temperatures over Tadham are most likely due

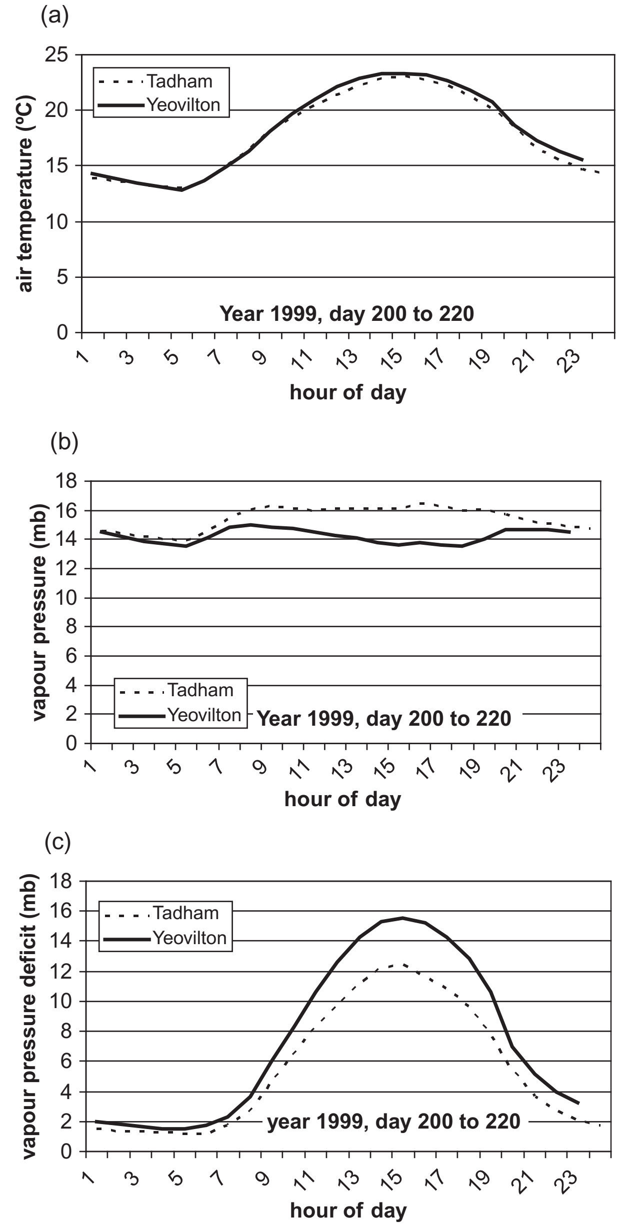

Fig. 4 Comparison of (a) air temperature, (b) vapour pressure, and (c) vapour pressure deficit within and outside the SLM (Tadham Moor and Yeovilton respectively).

to the extraction of energy from the over-passing air mass to help fuel the increased evaporation (latent heat fluxes).

It is assumed here that reduced temperatures are a benefit to humans and thus a positive ecosystem service. Lower summer temperatures are likely to be more comfortable for people working on, living in or visiting the SLM and for livestock. However, higher absolute humidity (and lower humidity deficit) is likely to be less favourable to humans, i.e. negative ecosystem service.

Floods It is widely recognized that wetland vegetation can slow the speed of water flow into rivers and streams (O'Connell *et al.* 2004) and the storage of floodwater on floodplains can reduce flood magnitude downstream (Bullock and Acreman 2003). For example, the UK *Flood Studies Report* (Natural Environment Research Council 1975) documented the attenuation of flood peaks on the River Wye by its floodplains. A modelling study of the River Cherwell in Oxfordshire (Acreman *et al.* 2003b) showed that separation of floodplains from the river by embankments increases the peak flows downstream by up to 150%. Mould (2008) showed that removal of floodplain storage at Otmoor (3.11×10^6 m^3 during the Easter 1998 floods) would have increased peak flows 13.7 km downstream on the River Cherwell at Oxford by 16%, and closer to the wetland system at Islip on the River Ray tributary (2.5 km downstream) by up to 200%.

Despite the dense network of drainage canals and pumping stations, the SLM are prone to flooding due to low-lying topography and limited hydraulic gradient. Many of the internationally recognized habitats, species and wildlife communities have established because of periodic inundation. The lower lying areas are sparsely populated and villages are sited on slightly higher land or on or behind embankments. There is nevertheless a flood risk to some towns and villages, such as Burrowbridge, Bridgwater and Taunton and infrastructure such as roads. Much farmland is also at high risk due to its location on floodplain wetlands. The strategic flood management approach for the SLM, as described in the Catchment Flood Management Plans (CFMPs) of the Parrett (EA 2008) and Axe/Brue (EA 2007), is to promote more sustainable flood risk management by better use of natural floodplain storage. CFMP Policy option 6 is to "take action to increase the frequency of flooding to deliver benefits locally or elsewhere, which may constitute an overall flood risk reduction". Within this context work must be undertaken to maintain the safety of embankments and infrastructure. The Parrett Catchment Project (Forum for the Future 2005) has sought to store floodwater temporarily in designated storage areas on farmland in the upper and mid-catchment wetlands until the peak flow of floodwater had passed. Four pilot schemes were developed, increasing effective storage capacity by 67 000 m^3, to demonstrate the approach and learn what is required to implement such schemes more widely. The volume of available storage varies with flood level; at 5 m AOD the floodplain of the Parrett (including Currymoor, Northmoor and Haymoor) has a storage volume of 6.8×10^6 m^3, inundating 17.1 km^2; at 7 m AOD the floodplain has 10×10^6 m^3 of storage (Catchment Futures 2008).

The flood water storage volume available in soils and ditches of the North Drain catchment (26.5 km^2) of the SLM was calculated using a GIS (Acreman *et al*. 2007, Mould 2008). They assumed that ditch water levels were at field level within the land parcels where owners had agreed to sustain Tier 3 ditch water levels (currently 0.68 km^2) and pumped to a low level in the remainder of the catchment (25.8 km^2). This water level was estimated at 0.57 m below field level from historical winter data (Fig. 3). The volume of storage available was estimated as 3.58×10^6 m^3; this does not include above ground water storage. Using methods following those in the *Flood Estimation Handbook* (Robson and Reed 1999), this equates to around 89% of the volume of the median annual maximum flood (V_{med}) for the catchment (3.8×10^6 m^3). This storage would be lost if all landowners in the catchment raised water levels to Tier 3, indicating a trade-off between flood management and wildlife conservation objectives. This study made two assumptions: first that all remaining wetland could be held at Tier 3 and second that flood water can penetrate rapidly from ditches into the intervening fields. The speed of water movement depends on many factors, such as the existence of macro-pores in soil that can transport water rapidly. If it is assumed that only an area three times the size of the current Tier 3 area could become Tier 3, and water would only penetrate rapidly 10 m into the fields from the ditches, the additional volume of lost storage would be 131 400 m^3 or 3.1% of V_{med}. It is noteworthy that this study represents an extreme case. as most of the North Drain catchment is wetland; in other catchments, wetlands are only usually a small proportion of the catchment (*e.g*. the Brue and Parrett catchments on SLM), thus the loss of storage would be a smaller percentage of the annual flood volume and possibly easy to mitigate through slightly increased above ground storage. Furthermore, compaction of the soil through lowering water levels may have lowered ground level and created more above ground storage.

Carbon budget The transfer of carbon between peatlands and the atmosphere as the greenhouse gases carbon dioxide (CO_2) and methane (CH_4) is important for regulating the global climate (Schulze *et al*. 2009). The wetland carbon pool is estimated at 37% of the 1943 Gt of carbon in the terrestrial biosphere pools (Bolin and Sukumar 2000). The fact that wetlands have accumulated carbon in peat in the past suggests that they may offer a potential climate change mitigation option for the future. However, a review of available European carbon budget data (Byrne *et al*. 2004) concluded that most peatland types vary between a small sink and a moderate source of GHGs, principally from a substantial CH_4 emission; none show unambiguous net uptake of GHG, thus even undamaged peatlands may have a net warming effect on climate, although restored fens and bogs have a much smaller effect than that for various types of pre-restoration management. Therefore, restoration has clear benefits in global warming terms over the un-restored case, even though restored peatlands may not have a net carbon sink function.

The net ecosystem exchange of CO_2 was measured by an eddy correlation system at Tadham Moor on the SLM in 2002 (Lloyd 2006). Results show that while 1568 g C m^{-2} were assimilated into the vegetation, only 1399 g C m^{-2} were respired from the combined vegetation and soil surface, leaving a balance of 169 g C m^{-2} and making the site an apparent sink for carbon. The measurements include the assimilation of CO_2 into the meadow vegetation, but not the loss of CO_2 that would have occurred if the vegetation had been left to senesce and decompose on site. Instead, the hay was harvested and taken away, and some of the new meadow growth was consumed by cattle, which removed vegetation in the form of increased body weight. From harvest yields and established relationships between cattle weight gain per kg of herbage eaten, it was estimated that 228 g C m^{-2} had been removed from the site. Subtracting this turned the field from a carbon sink to a carbon source losing 59 g C m^{-2} during the year. Had site water levels been maintained to the prescribed Tier 3 level, respiration losses would have been reduced by 243 g C m^{-2} over the year. Such an exercise shows that, notwithstanding a certain degree of uncertainty in this result, it is probably valid to say that adhering to the Tier 3 water management scheme could have reduced the carbon losses to such an extent as to make the field at least carbon neutral.

Water table levels were measured at the same time as CO_2 fluxes. However, to define the relationship between water table level and CO_2 fluxes, it is necessary to normalize the data for the effect of soil temperature on these same CO_2 fluxes. The relationship between R_{10} (the respiration rate at 10°C) and depth to water table was calculated by Lloyd (2006) using an equation defined Lloyd and Taylor (1994) and is shown in Fig. 5. The relationship is broadly linear, which may reflect some homogeneity of both the peat soil and the microbial communities within the soil.

It is noteworthy that there is an inherent circularity if depth to water table is used to equate R_{10}, which is subsequently used to calculate soil respiration based on soil temperature. To avoid this, R_{10} was set to 1.248 (as in equation 4 of Lloyd 2006) which is the estimated CO_2 soil respiration from at Tadham Moor with the water table close to the soil surface. Using this value provides both a baseline value for investigating the effect of water table level on CO_2 flux and normalizes the soil respiration values for soil temperature effects. Estimates of soil respiration were computed based on the soil temperatures at 30 cm (as

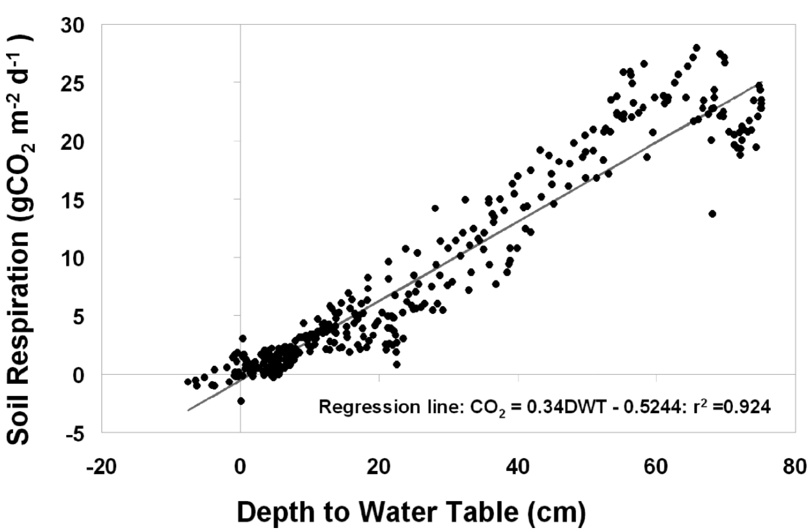

Fig. 5 Water table control on CO_2 flux at Tadham Moor, Somerset.

used by Lloyd 2006) as there is a complete record of soil temperatures at this depth and it also avoids the highly variable temperatures at the surface where thermal conductivity of wet or dry peat also plays a major factor in moderating soil temperatures. The computed values were then subtracted from the overall daily estimates of soil respiration to leave a component that depended largely on DWT.

Although raising water levels may make wetlands CO_2 sinks, they may emit large amounts of methane (CH_4). Persistently wet soils create anaerobic conditions that favour the activity of methanogenic bacteria, which produce and emit CH_4 from soils. In contrast, drier aerobic soils favour the activity of methanotrophic bacteria that oxidize CH_4 leading to soil CH_4 consumption. As these two microbial cohorts co-exist in soils in different ratios it is the net balance of their collective activities that lead to soils being either net sources or sinks of CH_4. One of the major determinants of wetland CH_4 fluxes is the water table depth. This defines the size of the aerobic CH_4 oxidation and anaerobic CH_4 production zones. Measurements of soil CH_4 fluxes were made at Tadham Moor during three hydrological phases i.e. summer August low water table, winter November surface-flooding and spring March post-flooding events during 2003 and 2004. Water tables were on average, respectively –81, +2 and –23 cm above or below the soils surface for these three campaigns.

Mean CH_4 fluxes were –85 (±1 SE 22), +19 (±1 SE 16) and –19 (±1 SE 13) μg CH_4 m^{-2} h^{-1} for the summer, winter and spring field campaigns, respectively. Strong relationships were apparent between water table depth and average CH_4 flux (Fig. 6) for each campaign ($R^2 = 0.79$; $P < 0.01$) such that a reduced water table resulted in net CH_4 consumption (a sink) rather than emission (a source). The critical water table level at which this switch takes place is around 10 cm below the soil surface. Overall, due to the water tables generally being below 10 cm during this study period the Tadham moor peat soil was a net sink for CH_4. When CH_4 fluxes were positive (winter), they were an order of magnitude less than measured fluxes from wetlands that have not had drainage management. For example, Bellisario *et al*. (1999) reported that the average CH_4 flux from five Canadian peatland sites (bog to rich fen) was 22 to 239 mg CH_4-C m^{-2} h^{-1}, while Huttunen *et al*. (2003) reported ranges of 81 to 230 mg CH_4 m^{-2} h^{-1} for eight Finnish minerotrophic

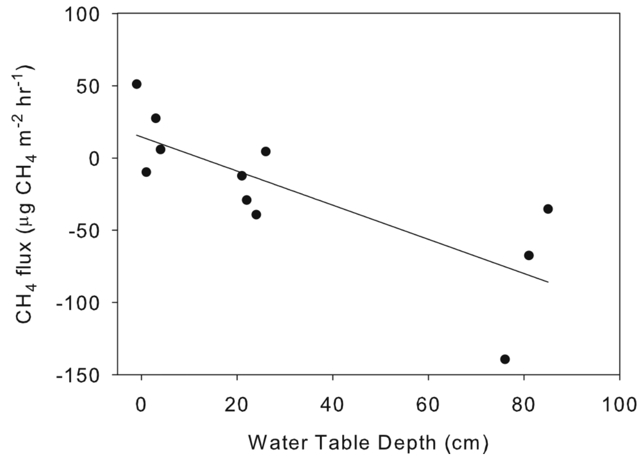

Fig. 6 Water table control on methane flux at Tadham Moor, Somerset.

fens. However, the current results are similar to fluxes from a drained minerotrophic fen ranging from –25 to 375 μg CH_4 m^{-2} h^{-1} (Augustin *et al*. 1998). Overall, the Tadham Moor results highlight the potential for soil water level management to control the soil CH_4 budget.

To explore the relative impacts of water table level on the emission of greenhouse gases from the soil, estimates of CO_2 and CH_4 fluxes were calculated with respect to their global warming potential. Table 1 shows that raising water levels to or above the ground leads to net greenhouse gas uptake by the wetland (a sink). On a molecule-for-molecule basis, CH_4 has a global warming potential 33 times that of CO_2 on a 100-year time scale (Shindell *et al*. 2009). This analysis of the balance of the gases on atmospheric radiative forcing suggests that CH_4, for the local fields investigated, plays a minor role compared to CO_2. However, what is not factored into these calculations are potential CH_4 emissions from the 200 km of drainage ditches that criss-cross the Somerset Levels. The limited available literature suggests that these ditches could be CH_4 emission hotspots (Van Den Pol-Van Dasselaar *et al*. 1998, Schrier-Uijl *et al*. 2008). Any future research in the SLM should commit to reducing the uncertainty in estimates of catchment CH_4 emissions through incorporating these less dominant but nevertheless potentially important locations.

Diseases The SLM are known particularly for the large numbers of waterbirds they support. However, migratory water birds—particularly ducks,

Table 1 Trade-off of greenhouse gas fluxes and the Global Warming Potential with water table level (+: source and –: sink) using the assumption that CH_4, on a molecule for molecule basis, has a GWP 33 times that of CO_2 on a 100-year time span (Shindell *et al*. 2009).

Depth to water table (cm)	CO_2	CH_4		Net GWP balance
	CO_2 kg ha^{-1} d^{-1}	CH_4 kg ha^{-1} d^{-1}	CH_4 kg ha^{-1} d^{-1} (as CO_2 equivalent)	
−10 (flooded)	−39	0.0063	0.2079	−38.8
0	−5	0.0030	0.099	−4.9
10	29	0.0007	0.0231	29
20	63	−0.0022	−0.0726	62.9
30	97	−0.0049	−0.1617	96.8
40	131	−0.0078	−0.2574	130.7
50	165	−0.0107	−0.3531	164.6
60	199	−0.0135	−0.4455	198.5
70	233	−0.0163	−0.5379	232.5
80	267	−0.0191	−0.6303	266.4

Table 2 Example water bird records for Somerset Levels and Moors (* species listed as at risk of exposure to H5N1 outside the EU by Snow *et al*. 2007).

Common name	Latin name	Mean numbers 1998–2002	% GB population
Tundra swan*	*Cygnus columbianus bewickii*	112	1.1
Eurasian teal*	*Anas crecca*	21231	5.3
Northern lapwing*	*Vanellus vanellus*	36580	1.0
Mute swan*	*Cygnus olor*	842	2.2
Eurasian wigeon*	*Anas Penelope*	25759	1.7
Northern pintail*	*Anas acuta*	927	1.5
Northern shoveler*	*Anas clypeata*	1094	2.7
Gadwall*	*Anas strepera strepera*	522	3.0
Water rail	*Rallus aquaticus*	36	8.0
European golden plover*	*Pluvialis apricaria*	3857	1.5
Ruff*	*Philomachus pugnax*	16	2.2
Common snipe*	*Gallinago gallinago*	1633	1.6

geese and swans—are the main dispersing agent for highly pathogenic strains of avian influenza at an intercontinental scale (Gilbert *et al*. 2008) and represent a key means by which the emergent H5N1 strain could be introduced into the British poultry industry (Snow *et al.* 2007). Some 24 migratory wild bird species winter in the UK that have a high probability of exposure to H5N1 outside the EU (Snow *et al*. 2007). Almost half of these species have significant populations on the SLM (Table 2), particularly lapwings, wigeons and teals. In 2008, an outbreak of the H5N1 virus was recorded in mute swan populations at Abbotsbury, Dorset (Defra 2008) >60km from the SLM. The H5N1 virus is more likely to be transmitted between wild birds and poultry where they are in direct contact. This is more likely in commercial operations with large flocks, consisting of geese and ducks rather than chickens and turkeys (since the former are fed outdoors), and with free-range or back-yard flocks as opposed to indoor flocks (Snow *et al*. 2007). Snow *et al*. (2007) mapped these poultry risk factors and integrated them with a wild bird risk score (based on abundance of key water bird species in several recent surveys) to generate a combined map of areas across the UK at highest risk of H5N1 incursion. Within this framework, Somerset was amongst the top-ranked counties with regards to risk of H5N1 incursion, with over 40% of the land area within the county identified as high priority for surveillance due to the coincidence of free-range flocks and wild bird populations (Crick *et al*. 2006). As a result, Somerset is listed amongst the priority counties for regular wild bird surveillance by sampling of shot, live-caught and dead birds (Defra

2010), illustrating how GIS-based frameworks can facilitate improved management of conflicts between ecosystem services. However, Somerset does not have the large intensive poultry farms seen in other areas with wetlands, such as East Anglia.

In other wetland systems, the abundance of mosquitoes has been shown to be reduced in the presence of the diverse communities of invertebrate predators (including *Dytiscus, Laccornis, Hydaticus* and *Hydrophilus* species) that tend to build up in older water bodies (Carlson et al. 2009). The role of predators versus other habitat factors in regulating the abundance and nuisance impact of mosquitoes on the SLM is currently under investigation in ditches with different clearance regimes. Key human-biting mosquitoes recently found on the SLM (S. Schäfer, CEH, unpublished data) include *Anopheles claviger*, a species capable of transmitting *Plasmodium vivax*, (the probable causal agent of historical malaria in the UK) and *Coquillettidia richiardii*, a species that bites humans and birds and is implicated as a bridge vector involved in West Nile virus transmission in the US (Medlock *et al*. 2005). Modelling work has demonstrated that areas of the south of England, including Somerset, are currently warm enough to support transmission of *P. vivax* for two to three months per year (Lindsay and Thomas 2001)—a period that is likely to extend with future warming. However, though warming may increase the development rates and survival of mosquitoes and pathogens, whether local transmission of malaria and other mosquito-borne pathogens occurs in wetland areas such as the SLM will additionally depend on: (i) the availability of breeding sites for key vectors; (ii) whether breeding sites coincide with areas in which people live or work; (iii) whether key mosquitoes are inclined to bite humans rather than livestock; and (iv) whether pathogens are introduced from areas in which they are circulating outside the UK. Given the current state of knowledge on mosquito habitat preferences, it is far from obvious whether raised water levels will have positive impacts on suitability of wetland breeding sites and increase levels of mosquito abundance. During the peak period of adult mosquito activity, between May and September, water levels are actually higher on pumped rather than Tier 3 sites—where levels are raised in winter (Fig. 3). Most sites on which wetlands are being recreated on the SLM are also reasonably remote from large population centres and mosquitoes produced in such site may cause limited biting nuisance to people in the foreseeable future.

Cultural services

History and archaeology In dryland sites, archaeological remains consist primarily of fragments of pottery, stone, glass and metal, since organic material rapidly decomposes. In wetlands, anaerobic conditions lead to the preservation of structural timbers and wooden or composite artefacts, such as bows, bowls, canoes and tools and weapons with wooden handles. The conservation of the archaeological and palaeoenvironmental remains is dependent upon sustainable management of the peat soils, including high water table levels to maintain anaerobic conditions (Smit *et al.* 2006). Holden *et al.* (2006) identified trigger points for conserving wet-preserved archaeological remains. Additionally, arable cultivation leads to rapid (2–3 cm per annum) peat wastage and associated destruction of cultural artefacts. Van de Noort *et al.* (2001) studied the rate of wetland heritage loss for England and estimated that up to 50% of the archaeological sites that existed in 1950 were lost by 2000. Assessment of the quality of nine archaeological sites in SLM showed that those in soils with a low pH and where a significant overburden of peat and/or clay is present were best preserved (Brunning 2001).

Excavations on the SLM have revealed many archaeological structures and other finds providing fairly detailed knowledge of human activity. The area contains more scheduled wetland prehistoric sites than the whole of the rest of England combined.

When the sea level rose and flooded the valleys of the SLM, it forced the Mesolithic people to occupy sites on islands and higher ground, indicated by scatters of flints. The Neolithic (*ca* 4000–2500 BC) people continued to exploit the wetlands for their natural resources and started to construct wooden trackways. Over 40 different trackways have been discovered; the best preserved in the UK is the Sweet Track, dating from 3806 BC to cross nearly 2 km of wetland that lay between dry land and a mid-marsh island in the SLM (Coles 1990). Its single plank walkway was held about 40 cm above the soft ground by pairs and groups of obliquely crossed pegs retained by a ground-level rail. The most complete representation of the material culture of the Iron Age (*ca* 750–0 BC) in the UK is the Glastonbury Lake Village (Adkins and Adkins 1992), inhabited by around 200 people living in 14 roundhouses. The wetland around the Isle of Avalon, the highland around Glastonbury (including the hill of Glastonbury Tor), is the legendary burial place of King Arthur and Guinevere, though there is no true archaeological evidence.

The waterlogged peat and clay deposits of the SLM also contain a wealth of palaeoenvironmental data in the form of plant and animal remains, such as pollen, seeds, snails, beetles, diatoms and foraminifera. These provide a unique record of the changing climate, sea level and landscape during the Holocene, such as during the Medieval Warm Period and the Little Ice Age (Howard *et al*. 2008). The peat deposits are up to 8.5 m thick and believed to contain the longest Holocene peat record of any lowland location in the UK.

Recreation, tourism and aesthetics Tourism within Somerset attracts 2.5 million staying visits each year generating around £409 million, whilst the total annual average spend by day visits is £623 million (SWT 2008). The main proportion of visitors tends to be concentrated in West Somerset, Sedgemoor and the coast. In rural areas, numbers are much lower. Despite it having 17 separately identifiable tourist attractions, Mills *et al*. (2000) described the SLM as "underdeveloped and recognition of the area as a tourist destination is low". The report finds that provision of footpath and bridleways is poor for historic reasons, and it estimates that the total visitor spend within the study area is only £2 million per annum. Sedgemoor District Council states that the area tends to attract visitors with specialist interests in walking, cycling, fishing or nature conservation. It is assumed here that these include appreciation of the SLM's landscape, including traditional practices of livestock rearing and dairy farming. South Somerset District Council and partners have initiated an 80-km walking route along the River Parrett designed to be a sustainable tourism route, although recent research indicates that this trail is primarily used by local people. Route 3 of the National Cycle Network (Lands End to Bristol) already passes through the SLM, using for example the disused railway track between Glastonbury and Highbridge. This cycle path is used by hundreds of locals and visitors each year. Much of the attraction of the route is the low-lying, open wetland landscape that offers wide views.

Bird-watching is a further major recreational activity in the SLM primarily for wetland birds. Around 70 000 visits per year are made to the reserves in SLM owned by the Royal Society for the Protection of Birds. Ham Wall reserve receives around 35 000 visits per year; a key feature of this site is the reed beds where some 6–10 millions of starlings roost every night during the winter. West Sedgemoor has some 15 000 visitors and Greylake 20 000 (Bridge, personal comm.)

In many wetlands, such as the Tonle Sap in Cambodia, fish provide the majority of food protein and thus fishing would be classed as a provisioning service (Lamberts 2006). In the SLM fishing is primarily a recreational activity, although some species such as trout and pike are eaten. The coarse fishery on the River Parrett varies from well above average for chub, roach and pike at Thorney Moor, to only minor populations of fish species and poor habitat at South Petherton (under the Freshwater Fish Directive—78/659/EEC). Surveys of the River Tone showed that eel, chub and brown trout feature significantly, although other species were also found such as dace and salmon par. Roach is the predominant species within the River Yeo, most originating from Sherborne Lake in the headwaters. The River Isle has populations of chub, dace and common bream, but only in minor numbers due to the predominantly low water levels (EA 2008).

No figures were available for the SLM itself, but in England and Wales 2.6 million people over 12 years old went fishing in freshwater in 2005, spending £2.7 billion and supporting 20 000 jobs (EA 2006). The SLM include a wide variety of river, canals, ponds and lakes that attract locals and tourists. Taunton angling association, which owns fishing rights on River Tone, West Sedgemoor Drain and the Bridgwater to Taunton canal, has 900 members paying between £5.50 and £34.50 per year for a license. Bridgwater and Weston-Super-Mare Angling Associations probably have similar numbers. In addition, there are many small private clubs for specimen fishing (especially carp and tench) that charge £6–20 per day.

Education Ham Wall offers a programme aimed at "inspiring and enthusing" visitors about the wildlife of the Avalon Marshes. Boardwalks, hides and viewing platforms enable groups to experience wetlands at close quarters. Guided walks and school group visits are available to Shapwick National Nature Reserves. Somerset Wildlife Trust runs its own programme of events on Westhay Moor SSSI (Site of Special Scientific Interest; see below) and, likewise, the RSPB on West Sedgemoor SSSI. Nature England's team newsletter for farmers and landowners runs regular features about the SLM. Interpretation facilities are available at the Peat Moors visitor centre adjacent to the Shapwick

National Nature Reserve. Interpretation panels have been located around the Reserve where appropriate. SWT have provided interpretation boards on Westhay Moor SSSI.

The Peat Moors visitors centre has three full size reconstructions of Iron Age roundhouses that have been created to give an insight into living conditions in the Glastonbury Lake Village. Here in particular, the ecosystem service is dependent on cultural heritage and human activity rather than the natural processes of wetlands. The centre closed in 2009 due to financial cutbacks at Somerset County Council, but a new Avalon Marshes Wetland Centre is proposed to enhance public access to and understanding of the unique natural and cultural heritage of the area.

Supporting services

Biological uniqueness and diversity Wetlands can be extremely species-rich; over 3500 species of invertebrates, 150 species of aquatic plant, 22 species of duck and 33 species of wader have been identified living in UK wetlands, whilst all six of our native species of amphibian depend on wetlands for breeding (Merritt 1994). A quarter to a third of the vascular flora occurs primarily in peaty wetlands; Wicken Fen in eastern England has over 8000 species recorded (http://www.wicken.org.uk/), including 121 species of Red Data Book invertebrates (Friday 1999).

Water birds particularly make use of wetlands during migration (Wetlands International 2009) using wetlands for feeding, roosting, and sheltering from adverse weather. The SLM are known particularly for the internationally important large numbers of waterbirds they attract during the winter and breeding seasons (Dawes and Leece 2002); the Ramsar designation (http://www.jncc.gov.uk) is based on, for example, a count of over 97 000 water birds per year from 1998/99 to 2002/03 and examples of individual species are given in Table 2.

The SLM represent the largest remaining area of lowland wet grassland in England (more than 20% of the resource). The mosaic of wetland habitats includes open water (ditches and ponds), reed-bed, damp heath, fen, wet grassland, carr and remnants of acid raised mire. Natural England has designated 18 Sites of Special Scientific Interest (SSSIs) covering 7200 ha, 12 of which (6300 ha) are Special Protection Areas under the European Habitats Directive. The SLM support a range of plant communities including species-poor grassland (e.g. perennial rye grass), with National Vegetation Classification (NVC) communities (Rodwell 1991–2000) MG13, MG6, MG7 and MG10. Where agricultural improvement has been less intense, species-rich fen meadows and flood pastures occur with MG8 *Cynosurus cristatus-Caltha palustris* grassland with *Cirsium dissectum* and *Caltha palustris* and mire communities (fen meadows) such as M23, M24 and M25 with *Molinia caerulea* and more *Juncus* and *Carex* species. Smaller areas of drier species-rich hay meadows (MG5) also occur with *Centaurea nigra, Orchis morio* and *Briza media*. The SLM also support limited areas of tall herb fen (S24) with *Lathyrus palustris, Peucedanum palustre* and *Thelypteris palustris* and small remnants of raised bogs, which are very degraded and support vegetation more akin to wet heath with *Erica tetralix* and *Molinia caerulea*. Open water, reed swamp and reedbed with a range of species from submerged plants to tall stands of *Phragmites australis* and *Typha latifolia* are found in the flooded peat workings as well as the drainage channels. Wet woodlands, where peat has been cut many years ago, are dominated by *Salix* spp., *Betula* spp. and *Alnus glutinosa*.

Analysis of the trends in the distribution of 18 plant species indicative of different plant communities or stages of agricultural improvement from the mid-nineteenth century to 1997 (Mountford 1994, Swetnam *et al*. 2004) showed decline throughout much of the 20th century due to lowering of winter water levels by pumping and subsequent desiccation of the wetlands, plus increase nutrient levels from fertilizer applications and peat extraction. However, later data (1980 and 1997) provide some evidence of the effectiveness of raising water levels under an agri-environment scheme (Environmentally Sensitive Area scheme) in terms of overall vegetation status and quality. Species totals had improved since 1986/87, with significant increases for many species including *Carex panicea, Cynosurus cristatus, Lotus pedunculatus, Lysimachia vulgaris, Mentha aquatica, Phragmites australis* and *Succisa pratensis.* Those species that have continued to decline are typical of non-agricultural habitats (fen, carr etc.) where the ESA has less influence. Most of the species that showed some apparent benefit from the introduction of the ESA are either constituents of farmed wet grasslands, or associated with the drainage channels that separate the fields (Mountford *et al*. 1999). It is likely that climate change will lead to summer desiccation of the wetlands and loss of important species (Somerset County Council 2009).

Grazing is an important management practice on wet grasslands to maintain particular communities (and species) of botanical interest such as MG8 *Cynosurus cristatus-Caltha palustris* grassland (Rodwell 1991–2000). However, grazing declined significantly over the past decade due to poor agricultural economics, which may allow the increase of communities that are less important botanically such as MG9 *Holcus lanatus-Deschampsia cespitosa* and MG10 *Holcus lanatus-Juncus effusus* rush-pasture, with a consequential decline in the nature conservation value of the SLM.

Detailed studies were undertaken at Tadham Moor to compare plant communities between wetland and dryland systems in experimental plots, some of which had previously been fertilised for four (N^-) or seven (N^+) years (Mountford *et al*. 2001). This was achieved by raising ditch water levels to Tier 3 (mean field level in the winter and 300 mm below this level in the summer). Raised water-levels led to a decline in the species typical of semi-natural old hay meadows. Increased aeration stress in the raised water level plots produced an initial sward die-back and spread of *Agrostis stolonifera* (a competitive ruderal species with a wide tolerance of water regimes) which subsequently declined to be replaced by a species-poor swamp with *Carex riparia, Glyceria* spp, *Ranunculus repens* and the moss *Calliergonella cuspidata*. In the short term there was some loss of plant diversity as species favouring dry conditions disappeared. Their replacement with wetland species and the speed of recovery of plant diversity depends on the availability of seeds and propogules. However, in the long term botanical diversity in the wetland is likely to be greater with raised water levels. Some impact of previous fertiliser treatments was detectable up to seven years after the cessation of fertiliser application (2000 in the N^+ plots and 1996/97 in the N^- plots). Those plots that received high levels of nitrogen for seven years continued to show higher cover of certain grasses, and reduced cover of low forbs.

There was some interaction between altered water-regime and past fertiliser treatment, and it appeared that the previous agricultural management altered the invasibility of the community, favouring certain species. Within the span of the experiment, the implementation of raised water levels led to the partial replacement of an old meadow vegetation (NVC: MG5 and MG8) by a ruderal community (NVC: OV28), swamp (NVC: S6, S22) or inundation grassland (NVC: MG13) (Rodwell 1991–2000).

Overall, application of raised water-levels to areas with high botanical (or invertebrate) biodiversity value should be exercised with caution, and consideration given to alternative prescriptions for increasing site wetness, especially with regard to avoiding anoxia and sward death at the start of the growing season. As with other ecosystem services, there is a trade-off in biodiversity but in this case not only in terms of biodiversity versus flood control but also within elements of biodiversity (birds *versus* plants/invertebrates).

Pollination In the UK, both managed and wild insects (bees, butterflies, moths, flies, beetles and wasps) contribute significantly to the pollination of a large array of crops and wild plants. As an ecosystem service, insect pollination directly contributes an estimated £440m per year to the UK economy through crop pollination (Postnote 2010) and is considered critical to the maintenance of current levels of crop production (Klein *et al*. 2007, Gallai *et al*. 2009, Winfree *et al*. 2009). However it is also essential for maintaining biodiversity and thus underpins other ecosystem functions. Over 70% of UK plant species are insect-pollinated and reduced pollination services can have detrimental effects on the dynamics and persistence of wild plant species and communities (Fontaine *et al.* 2006), as illustrated by the recent collapse in honey-bee populations in the USA (Stokstad 2007). In the UK and Europe, as in other parts of the world, wide-scale declines in many insect pollinators have been observed, as have concomitant declines in plant populations (Biesmeijer *et al.* 2006, Carvell *et al.* 2006, Stokstad 2007). One of the main drivers of pollinator loss is the destruction of natural and semi-natural habitats (Kremen *et al*. 2007) resulting from agricultural intensification and land-use change.

The matrix of semi-natural habitats in the SLM provides abundant food and nesting resources that help maintain pollinating insect populations for the wetlands and surrounding landscape including cropping systems. For example, orchards remain a special feature in the SLM and benefit disproportionately from wild pollination (especially bumblebees and solitary bees in the genera *Andrena* and *Osmia*) for successful fruit production. Species-rich fen meadows and flood pastures, together with the banks of rhynes and other watercourses, are particularly important since they are rich in nectar and pollen sources. Although much of the SLM result from agricultural improvements and land drainage they support an abundant and diverse pollinator fauna, which includes some nationally rare species. Of particular note are four scarce bees including three bumblebees identified on the UK Biodiversity Action Plan: *Bombus sylvarum*, (now limited to the Somerset Levels, Salisbury Plain and the Thames Estuary), *B. muscorum* (widespread in the SLM), *B. ruderarius* (infrequent in the SLM) and the rare mining bee *Andrena lathyri*, last seen in 1950. The SLM are also important for nationally rare butterflies and moths. These include species found in fen meadows like the Marsh Fritillary (*Eurodryas aurinia)* which has a small population in the SLM and is rapidly declining elsewhere in the UK and the Narrow bordered Bee Hawk-moth (*Hemaris tityus*). In addition other habitats like wet woodlands are important to species like the White Admiral (*Ladoga camilla)* which is restricted to southern England but has several populations in the SLM.

SYNERGIES BETWEEN ECOSYSTEM SERVICES

The information provided above describes individual ecosystem services of the peat wetlands of the SLM. It is clear that these wetlands are part of a socially, economically and ecologically important landscape. Of particular interest to policy makers is the combination of services that enable the collective implications of wetland management and restoration to be evaluated. In many cases the services are independent; for example there is little relationship between fishing and archaeology. Some services strongly reinforce each other, for example the existence of archaeological relics increases the educational services of the wetland and the diversity of bird species increases the tourist service.

As described above, the flood water storage volumes calculated for the North Drain catchment assume that water table levels as low, i.e. pumped to 0.57 m below mean field level during the winter. It is clear that should all land owners raise water levels to Tier 3 (mean field level during the winter) at the time of the flood, then 3.6×10^6 m^3 of storage would not be available. Table 3 summaries the ecosystem services and defines the synergies and potential trade-off relationships that exist.

Table 3 shows that most ecosystem services are based on wetland being wet; consequently the services are consistent and mutually consistent. The exceptions are flood storage and methane emissions. Flood storage is maximized under dry conditions. Whilst large volumes of above-ground flood water storage would still exist under raised water levels, the below ground storage, in soils and ditches, will be full and not available for flood water. Thus, raised water levels could potentially reduce flood storage. Additionally, raising water levels may decrease CO_2 emissions, but may increase CH_4 production, impacting on global climate change. Further analysis is required to quantify the total greenhouse gas and carbon balance trade-off between CO_2 and methane production for the SLM.

ASSESSING POSSIBLE FUTURE MANAGEMENT OPTIONS

Analysis of the physical, chemical and biological process in the SLM, has defined relationship between ecosystem services and management practices, which offers the potential to asses the implications of different management scenarios. These scenarios represent different potential futures for the SLM, and do not necessarily represent any agreed or even proposed objectives. A set of scenarios was defined for an analysis of peat wetlands across the UK (Bonn *et al*. 2009) as follows.

– *Raising water levels*: Extending Tier 3 raised water levels (Fig. 3) across most of the SLM.
– *Scrub clearance*: Removal of vegetation, particularly woody species, and those more representative of, or that will lead to, drier conditions through increased evaporation.
– *Removal of farm animals*: Cessation of use of the SLM for grazing dairy and meat livestock.
– *Increased grazing*: More intensive and/or widespread grazing by dairy and meat livestock, requiring pumped water levels (Fig. 3).
– *Increased arable land*: Ploughing of large areas of the SLM to grow arable crops, requiring pumped water levels (Fig. 3) to permit use of machinery.
– *Peat extraction*: Granting of licences to remove large volumes of peat for horticulture and/or fuel.
– *Carbon sequestration*: Land management to maximize carbon uptake by the wetlands (it is assumed this would be associated with higher water levels).

These scenarios and their implications for ecosystem services on the SLM are presented in Table 4, based on best available scientific knowledge. Water level control is the primary management tool employed on the SLM. Raised water levels, to Tier 3, generally increase desirable ecosystem services and thus provide the best trade-off, although they may

Table 3 Ecosystem services of Somerset Levels and Moors wetlands.

Service type	Service	Benefits to people/synergies	Limitations/trade-off
Provisioning services	Food	Livestock grazing	Nutrient content of natural grass lower than improved grass -Improved livestock grazing may mean lower biodiversity
	Freshwater	Freshwater available	Resource less with higher water levels, more wet grassland and reed area
	Peat	Fuel and horticulture resource available	Peat not renewable in the short term; loss of peat results in loss of many other services
	Withy and teasel products	Wetland provide withies for basket making and teasels for textile production	More land for withies and teasels may mean less land for grazing and natural habitats
Regulating services	Microclimate	Wetlands modify their own climate	Synergy with services supported by high water levels
	Floods	Flood storage available	Flood water storage assumes low ditch water levels before the flood
	Carbon	Wetlands have potential to sequestrate carbon	High water levels reduce CO_2 emissions and increase biodiversity but increase methane emissions
	Diseases	Wet conditions may alter the abundance of disease vector and nuisance insects	High water levels may increase disease vector habitat
Cultural services	Archaeology	Anaerobic conditions preserves organic matter	Synergy with services supported by high water levels
	Recreation	Wetlands provide a landscape and birdlife favoured by many people and angling	Synergy with services supported by high water levels
	Education	Wetlands provide range of scientific, social, economic educational subjects	Education is supported by archaeology
Supporting services	Biodiversity	Wetlands support unique plants and animals	Species may be less diverse with high water levels though different species and communities respond differently

Table 4 Implications for ecosystem services of management scenarios. Each cell describes the impact (increased, neutral, decreased) of each scenario (columns) on the ecosystem services (rows).

Scenario /Service	Raising water levels	Scrub clearance	Removal of farm animals	Increased grazing	Increased arable	Peat extraction	Carbon sequestration
Food (dairy and beef)	Reduced—lower grass nutrition	Increased—more farm land available	Reduced—food is primarily farmed animals	Increased—improved grass is higher in nutrient	Neutral—replacement of dairy and beef products with vegetables	Reduced—loss of farm land to peat extraction	Reduced—higher water levels reduce grass nutrition
Freshwater	Reduced—higher evaporation	Neutral	Increased—less nutrient pollution	Reduced—higher nutrient pollution	Reduced—higher nutrient pollution	Increased—lower evaporation	Reduced—higher evaporation
Peat (for fuel and horticulture)	Increased—reduced peat loss possible peat formation	Increased—reduced peat loss, possible peat formation	Increased—greater peat formation	Reduced—less peat formation (peat loss if water levels lowered)	Reduced—loss of peat	Reduced resource but increase in jobs in extraction	Increased—peat formation
Withies and teasels	Increased—more land for withies and teasel	Increased—more land for withies and teasel	Increased—more land for withies and teasel	Reduced—less land for withies and teasel	Reduced—less land for withies and teasel	Reduced—less land for withies and teasel	Neutral
Microclimate	Increased—higher evaporation increases micro climate alteration	Neutral	Neutral	Neutral	Reduced—lower evaporation reduces micro climate alteration	Reduced—lower evaporation reduces local climate cooling	Increased—higher evaporation cools the air locally
Floods	Reduced—less flood storage	Increased—scrub clearance reduces friction and increases flood conveyance	Increased—less soil compaction	Increased—lower water levels increase flood storage	Increased—if lower water levels, then increased flood storage	Increased—lower water levels and depressions increase flood storage	Reduced—higher water levels to retain carbon reduce flood storage
Carbon	Increased—higher water levels increases carbon sequestration	Neutral or reduced as woody species may sequestrate more carbon	Increased—more vegetation for peat accumulation	Reduced—less vegetation for peat accumulation	Reduced—less vegetation for peat accumulation	Reduced—less peat	Increased

Diseases	Impacts on vectors depends on whether increased water levels coincides with breeding period	Neutral (uncertain)	Increased if bites of vectors are diverted from cattle to humans (uncertain)	Reduced if bites of vectors are from humans to cattle (uncertain)	Reduced—if lower water levels during the mosquito breeding season, then fewer vectors (uncertain)	Reduced—lower water levels then fewer vectors (uncertain)	Increased—higher water levels more vectors (uncertain)
Archaeology	Increased—higher water levels protects sites and information held in peat	Neutral	Neutral or increased through reduced compaction	Neutral	Reduced—destruction of sites and information held in peat	Reduced—destruction of sites and information held in peat	Neutral—possible less disturbance to sites, but loss of historical landscape
Recreation	Increased—more natural environment	Increased—(improved visualization of historical landscape)	Reduced—but loss of cultural heritage landscape	Reduced—fewer characteristic species	Reduced—fewer characteristic species	Reduced—less natural environment	Increased –more natural environment
Education	Increased—more natural environment	Increased—more natural environment	Increased—more natural environment, but loss of cultural heritage	Reduced—fewer characteristic species	Reduced—fewer characteristic species	Reduced—less natural environment	Increased –more natural environment
Biodiversity	Decrease in short term, increased in long term; better for wetland species, some loss of terrestrial species	Increased—less competition for characteristic wetland species	Decrease in species dependent on grazing	Increase in species dependent on grazing (where grazing is appropriate)	Reduced—fewer characteristic wetland species	Reduced—fewer unique species	Reduced–more woody species

lead to reduced grazing nutrition and water resources (due to high evaporation) and less flood-water storage, as well as localized loss of terrestrial species, which may be highly regarded. Shrub clearance is practiced on some nature reserves, but scrub is generally not an issue on farmland due to grazing and ploughing. Clearance reduces competition for space for natural wetland species, but is broadly neutral for other services. Woody species may provide more carbon sequestration as they do not decompose as quickly as sphagnum species under warmer climates. Removal of farm animals will reduce food production drastically. Furthermore, most of the species that the SSSIs/SPA/Ramsar sites are designated to protect (e.g. birds and plant communities) are highly dependent on grazing to maintain their competitiveness. Therefore the removal of farm animals would have a detrimental effect on this biodiversity. However, grazing needs to be appropriate; too much grazing may often lead to land degradation and the loss of biodiversity, while too little grazing may lead to succession from grassland to woodland and the loss of the grassland habitat. Not only is the level of grazing important, but also the timing and the animals species involved (Watkinson and Ormerod 2001). In addition, many people see farm animals as part of the cultural heritage of the SLM; so such cultural values may be lost or reduced with removal of farm animals. Increasing grazing or arable land will provide more food, but the latter in particular will require low water levels which will negatively affect other services, such as carbon accumulation. If increases in grazing or arable land are associated with higher fertilizer or pesticide application, water resources may be detrimentally affected due to quality problems. Increased peat extraction would be positive only for peat extraction itself, with the additional benefits of employment in the extractive industry, but negative for other services. Increasing carbon sequestration may be beneficial for the SLM overall, as a peat soil-based wetland, but may have negative implications directly for food production and indirectly for water resources and flood storage through higher water levels. The increases in peat under scenarios of raised water levels and carbon sequestration refer to the peat resource itself; exploiting the peat as a service would require temporary lowering of water levels during the mining phase, which would not be compatible with carbon sequestration.

In the longer term, climate change is likely to have severe consequences for SLM. Mitchell *et al.* (2006) summarize the direct effects of climate change on aquatic and wetland habitats, including increased summer temperature, increased winter temperature, earlier onset of spring, increased summer drought, wetter winters, sea-level rise and increased flooding. Rising sea levels will increase the period of tide lock making it more difficult to discharge water into the estuary. This problem is likely to be intensified by a predicted increase in total winter rainfall and an increase in more extreme rainfall events. In addition, increasingly hotter and drier summers, may mean that there is insufficient water to maintain high water levels in summer and autumn (Acreman *et al.* 2009). This is already the case in hot summers when most rivers stop discharging to tidal waters and all flow from the uplands is diverted into the wetlands. In terms of ecosystem services of the SLM, climate change is likely to lead to lower water availability, less peat formation, reduced recreation, loss of archaeology and biodiversity and increased CO_2 emissions. For example, hotter summers are likely to be to the detriment of internationally important ditch invertebrate assemblages and lead to increasing peat wastage and damage to wetland archaeology (Somerset Water and Wetlands Habitat Action Plan 2009).

CONCLUSIONS

The UK government has recognized the need for better appreciation of "value to society" in land governance mechanisms, where the concept of value is broad and encompasses the full range of ecosystem services, whether or not they are marketed (Foresight Land Use Futures Project 2010). Decisions should take account of the full value of land in alternative uses, assessed on a consistent basis by decision-makers at different spatial levels and in different sectors. This study demonstrates that the ecosystem services of the SLM wetlands contribute substantially to the regional economy and the quality of life of local residents and visitors and support the implementation of wise use (Maltby 1992) and sustainable catchment management (Acreman and Mountford 2009). It highlights the trade-offs between different land management practices. The primary ecosystem services of the SLM are food production, conservation of peat soils to retain carbon and preserve archaeological sites and conservation of birds and plants for recreation. Water level control is the primary management tool and these services are optimized by maintaining high water levels (Tier 3; Fig. 3), although this may reduce grazing yields compared to drier conditions and may generate methane, marginally reduce flood management potential and create a heightened risk of diseases, such as avian influenza. Increasing carbon sequestration may require increased areas of woody species that decompose more slowly than grass, sedge and sphagnum. Predicted climate change may make maintenance of high water levels increasingly difficult. The study thus also highlights the trade-off, demonstrating that not all services can be maximized simultaneously and some would not want to be.

Acknowledgements The authors are grateful to Prof. Edward Maltby (University of Liverpool), David Leach (Brue Valley Living Landscape Project Manager), Philip Brewin (Brue Drainage Boards) and an anonymous referee for providing constructive advice on the draft manuscripts.

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