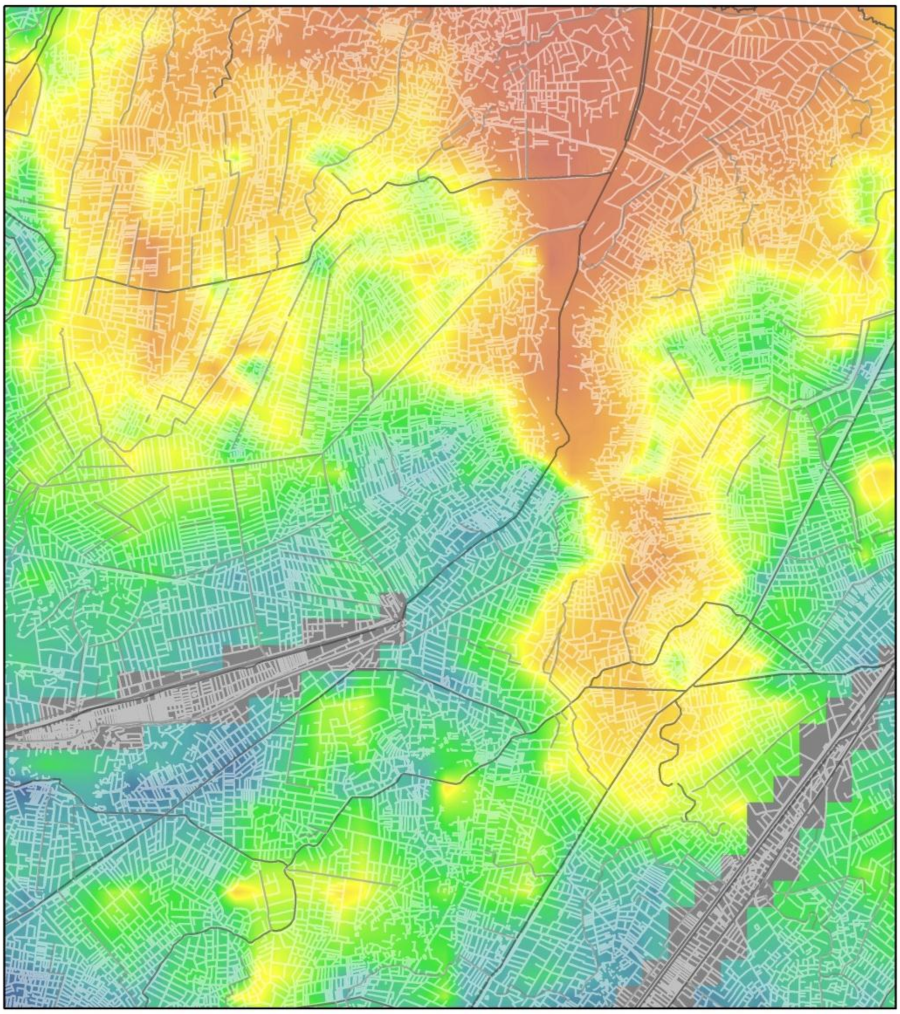
Predictive modelling of spatial biodiversity data to support ecological network mapping: a case study in the Fens



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Acknowledgements
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Cover picture: Extract of a map showing the predicted distribution of biodiversity.

Contents

Executive summary

The Fens were formally England's largest wetland, but the remaining 1% of wetland habitat is highly fragmented within an intensive managed agricultural landscape. A key goal of the Fens for the Future Partnership is to develop an enhanced and sustainable ecological network, linking fragmented habitat and increasing area. Within the arable landscape there are more than 20 million km of ditches and drains and, with the application enhanced management, this ditch network presents an excellent opportunity for both increasing habitat area and connectivity. However, ditch enhancement must be targeted to where it will be most effective and the aim of this study was to provide an evidence base for such strategic targeting.

The approach of this study was to analyse the available biological data, and extrapolate patterns in the distribution of wetland indicator species using environmental and geographic information, in order to predict the 'true' quality of the ditch network across the fen, having accounted for differences in recording effort. The maps of predicted wetland biodiversity richness were then compared to the ecological network proposed by the Fens for the Future project.

The biodiversity value of the landscape was greater close to existing wetland SSSIs. This may be due to SSSIs acting as reservoirs of wetland species or because environmental conditions, such as water quality, are better closer to those sites. Wetland biodiversity value was low in areas dominated by silty soils, such as those around The Wash; the distribution of peat soils was not an important determinant. Main river channels were predicted to have high biodiversity richness

Targeting conservation action towards connecting and managing areas of current high predicted biodiversity would increase resilience by allowing movement of species through areas of high biodiversity value and by increasing the overall size of such areas. The predicted distribution of biodiversity value suggests that the currently proposed network of corridors is generally well placed; this may be due to the focus on main rivers and drains. However, several secondary corridors pass through areas of low wetland biodiversity value and there is likely to be added biodiversity benefit from targeting other higher value areas for management. The maps of predicted biodiversity value can be used to strategically target areas of high biodiversity value for ditch enhancement and management.

Introduction

It is now well-recognised that there is a pressing need for a more evidence-based approach to strategic conservation delivery. The Lawton report (Lawton et al. 2010) sets out clear targets for conservation; these follow the simple idea of better, bigger, joined, recognising the importance of increasing landscape scale connectivity to enhance biodiversity resilience. One of the main goals of the Fens for the Future Partnership is to "*develop and establish an enhanced and sustainable ecological network*". The Fens were formally England's largest wetland, but the remaining 1% of wetland habitat is now fragmented within the country's most important agricultural landscape. However, criss-crossing the arable landscape are more than 20 million km of ditches and drains. With the application of more environmentally friendly farming practices and enhanced management, the ditch network presents an excellent opportunity for both increasing habitat area and connectivity for wetland species. The ditch network has the potential to be suitable for a range of wetland, littoral or aquatic species Audit (Mossman et al. 2012). However, such ditch enhancement should be targeted where it will be most effective, with preference given to those areas that have the greatest existing biodiversity value, and those areas whose location (in terms of geographic placement and underlying soils) give them higher potential biodiversity quality. The aim of this study was to provide an evidence base for such strategic targeting.

The approach of this study was to analyse existing biological data to model the current spatial distribution of biodiversity indicators in the arable ditch network. By relating indicators of ditch quality to environmental factors and the location within the fen basin this has potential to identify those parts of the ditch network of greatest conservation value, to support strategic spatial planning. The biodiversity indicators include Odonata species, wetland and aquatic plant species; species of conservation priority assigned to littoral, aquatic and wetland management guilds by the Fens Biodiversity Audit (Mossman et al. 2012), and Fen Specialists (species for which the fens is particularly important in terms of their UK range extent). Recording effort across the Fens landscape is highly variable, with many areas receiving little recording. Therefore, the mapped distribution of recorded species richness would not allow reliable assessment of the potential benefits of enhanced ditch management. Our approach was to analyse the available biological data, and extrapolate patterns using environmental and geographic information, in order to predict the 'true' quality of the ditch network across the fen, having accounted for differences in recording effort.

This study will allow the evaluation of those elements of the ecological networks already proposed by the Fens for the Future project (core areas, corridors, restoration areas, and sustainable use areas), and will provide evidence to support planning of buffer zones and stepping stones, that were proposed but not yet identified by the Fens for the Future project. The key elements of the proposed network are mapped in Fig. 15.

Methodology

Biological data

Biological records were collated from all 1 km squares wholly or partly within the Fens Natural Character Area boundary, plus an extension to include Chippenham Fen, following Mossman et al. (2012) – totalling, 4147 1-km squares. The majority of records were derived from those collated in the Fens Biodiversity Audit database (Mossman et al. 2012), supplemented by 58,701 plant records (2006 to March 2013) from the on-going Fenland Flora survey (Mountford & Graham, unpublished). The resulting database comprised 1,027,837 records.

To ensure modelling reflected the current or recent distribution of biological quality, records made prior to 1987 were excluded, following the Fens Biodiversity Audit. This threshold represents a trade-off between restricting analysis to the most recent data, and retaining a sufficient volume of records to allow robust spatial analysis.

Analysis was conducted at the scale of the 1 km square, aggregating all records within each square as an individual sample of replication.

Recording effort was greatest in the key wetland SSSIs, such as Wicken and Chippenham Fens (Fig. 1). In the wider landscape, recording effort was higher in Norfolk and Suffolk, compared to Lincolnshire and Cambridgeshire, due to the recent compilation of local and county floras. There were 497 1-km squares with no records; these were spread across Lincolnshire and Cambridgeshire.

Indicators of ditch network biological quality analysed as response variables

After compiling biological records for each 1 km square, taxanomic and biological response variables were selected for modelling, according to the following criteria: good indicators of ditch quality, and relatively well and widely recorded groups.

The following biological response variables were therefore selected for modelling:

- Odonata (dragonflies and damselflies) species richness
- Richness of Fens specialist species
- Total richness of conservation priority species from all 'wet' management guilds
- Total richness of conservation priority species from aquatic management guilds
- Total richness of conservation priority species from littoral management guilds
- Total richness of all wetland plant species
- Total richness of all aquatic plant species.

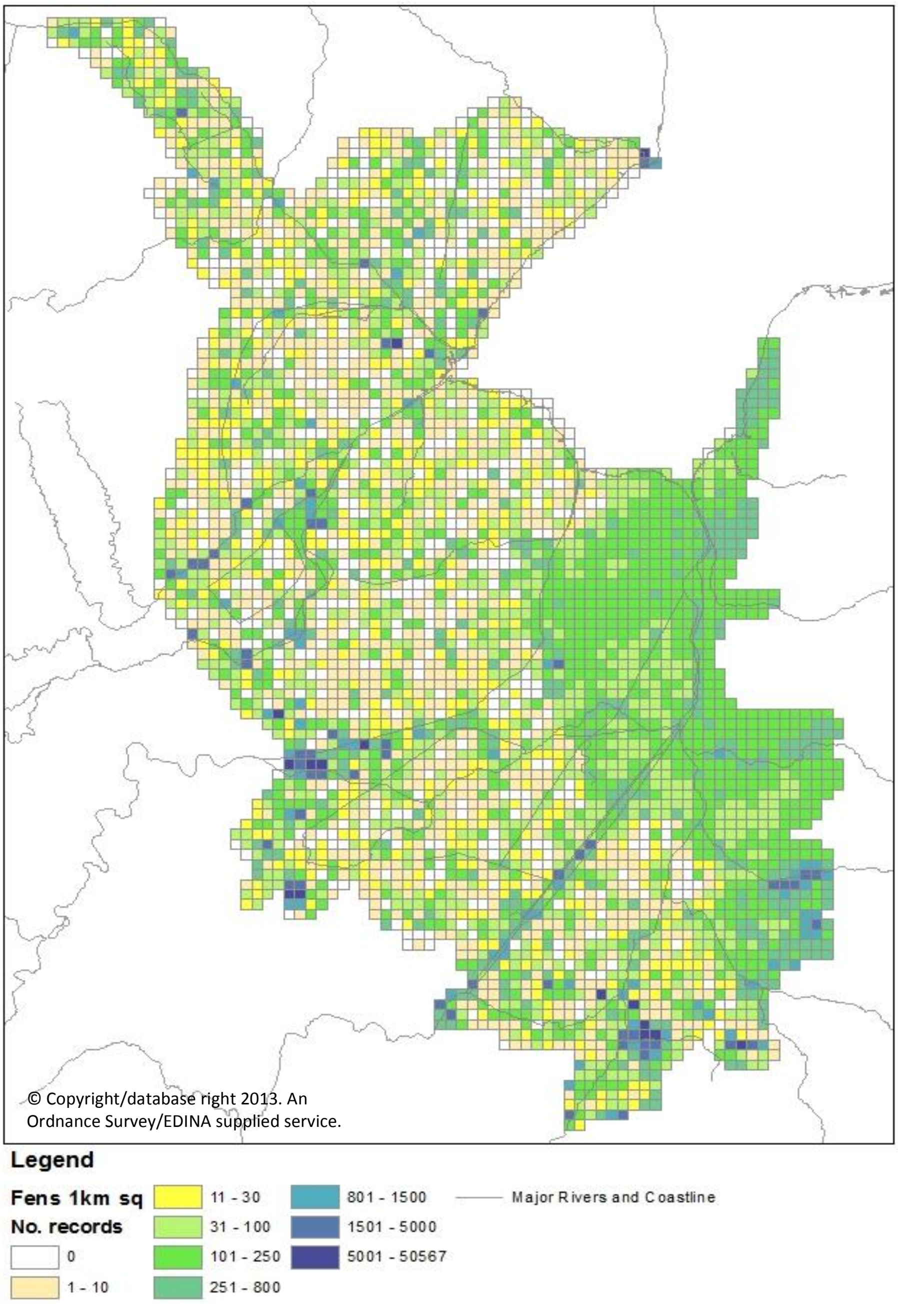


Fig. 1. Distribution of biological records made ≥1987 in the Fens NCA.

Odonata
Twenty-nine dragonfly and damselfly species have been recorded in the area ≥ 1987 (Appendix 1); all species were included in the analysis. Odonata were selected because they are a particularly well-recorded group. Fig. 2a shows the richness of Odonata species in the Fens NCA.

Fens specialist species
Fens specialists include invertebrate and plant species identified by the Fens Biodiversity Audit as being entirely or largely restricted, or that have a primary or secondary stronghold in the Fens. A full list of Fen specialist species is given in Mossman et al. (2012). Fifty-eight of the 81 Fens Specialists were recorded ≥ 1987. The richness of Fens specialist species was selected as an appropriate measure because they were considered good indicators of quality fen-type habitats and as their conservation is essential in the region. Fig. 5 shows the recorded richness of Fen Specialist species in the Fens NCA.

Priority species from management guilds
Multi-taxa management guilds, comprising species considered as priorities for conservation (specialist and designated species) that have shared requirements for conservation management actions, were identified by the Fens Biodiversity Audit. All priority species from aquatic (90 species, Fig. 3a) and littoral (109 species, Fig. 3b) guilds were used for modelling. Species from all management guilds associated with wetland habitats (372 species) were also selected (Fig. 2b). A list of guilds defined as aquatic, littoral or associated with wetland habitats is given in Appendix 2.

Wetland and aquatic plant species
Plants are one of the most widely recorded groups, and are considered good indicators of habitat quality. The richness of all 'wetland' plant species was used as a response variable, including the more common as well as rare or priority species. 'Wetland' was used as a broad term indicating plants that are associated with *any* wet or permanently damp conditions. Wetland plants were selected from the full UK flora (Hill et al. 2004) and identified as those vascular plant species that have wet or damp (≥7) Ellenberg moisture values, indicating a preference for wet conditions, **and** are associated with freshwater (aquatic, wetland or seasonally wet) habitat types. Plants of wet saline habitats were excluded for the purpose of the strategic network to provide connectivity for fen biota.

Ellenberg moisture value of 7 indicates that a species largely occurs on constantly moist or damp, but not wet soils (e.g. *Carex ovalis*, *Dactylorhiza maculata*), and the maximum value of 12 indicates a fully submerged species (e.g. *Potamogeton crispus*, *Ranunculus circinatus*). The additional criteria, that species must be associated with selected habitats, was used because species often have wider tolerances of soil moisture than denoted by Ellenberg moisture values. Furthermore, the second criteria allowed the filtering of species with Ellenberg values ≥7 but that are not associated with freshwater wetland habitats, e.g. that are instead saltmarsh or dune species. Species were required to be associated with at least one of eight selected habitats: acid grassland, calcareous grassland, improved grassland, neutral grassland, fen, bog, standing water and running water. The grassland habitats were selected to allow the identification of species associated with damp, wet and seasonally inundated grasslands, including habitats disturbed by fluctuating water levels, livestock or vehicles, such as *Fritillaria meleagris, Mentha pulegium, Juncus compressus.*

A total of 460 vascular plant species where identified as wetland plants, of which 271 species recorded in the Fens ≥1987 (Appendix 3). In addition to the vascular plants, all stonewort species (15 species) and any species of *Potamogeton* (16 species) were included, following Palmer et al. (2010), JNCC (2005) and Mountford and Arnold (2006).

To provide an alternative indicator, a sub-set of the wetland plants were selected that were considered to be fully aquatic. These included vascular plants, stoneworts and *Potamogeton* species associated with ditches. Classification of these 'aquatic ditch' species was based on existing lists by Palmer et al. (2010), JNCC (2005) and the Fenland-focused arable ditch scoping study (Mountford and Arnold 2006). A total of 163 vascular plant species, of which 133 were recorded in the Fens≥1987, all stonewort species (15) and all *Potamogeton* species (16), were selected (Appendix 3).

Figs. 4a and b show the recorded richness of wetland and aquatic plant species in the Fens NCA, respectively.

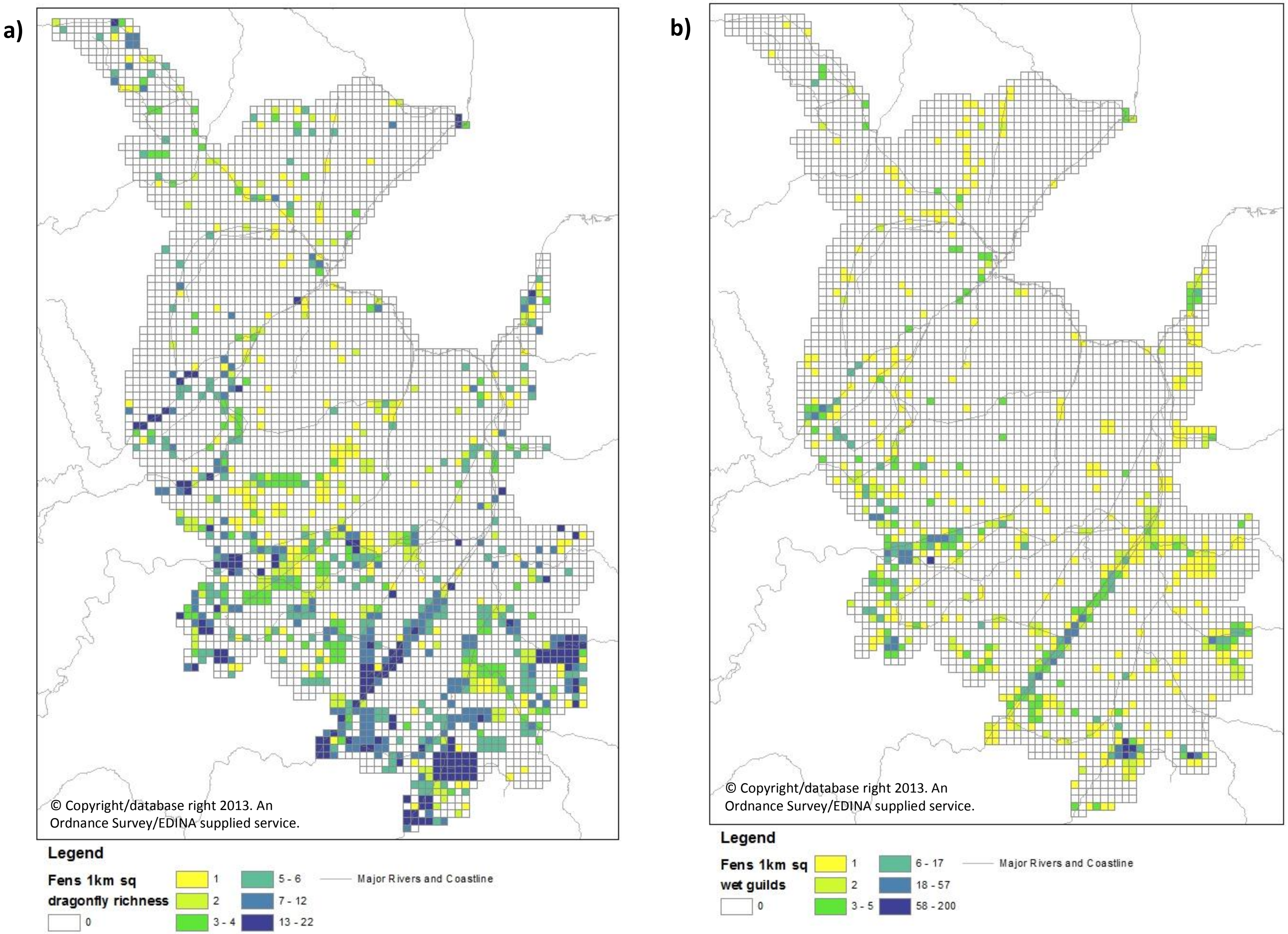


Fig. 2. Richness of a) dragonfly species and b) species from management guilds associated with wetland habitats, recorded in each 1 km square in the Fens NCA.

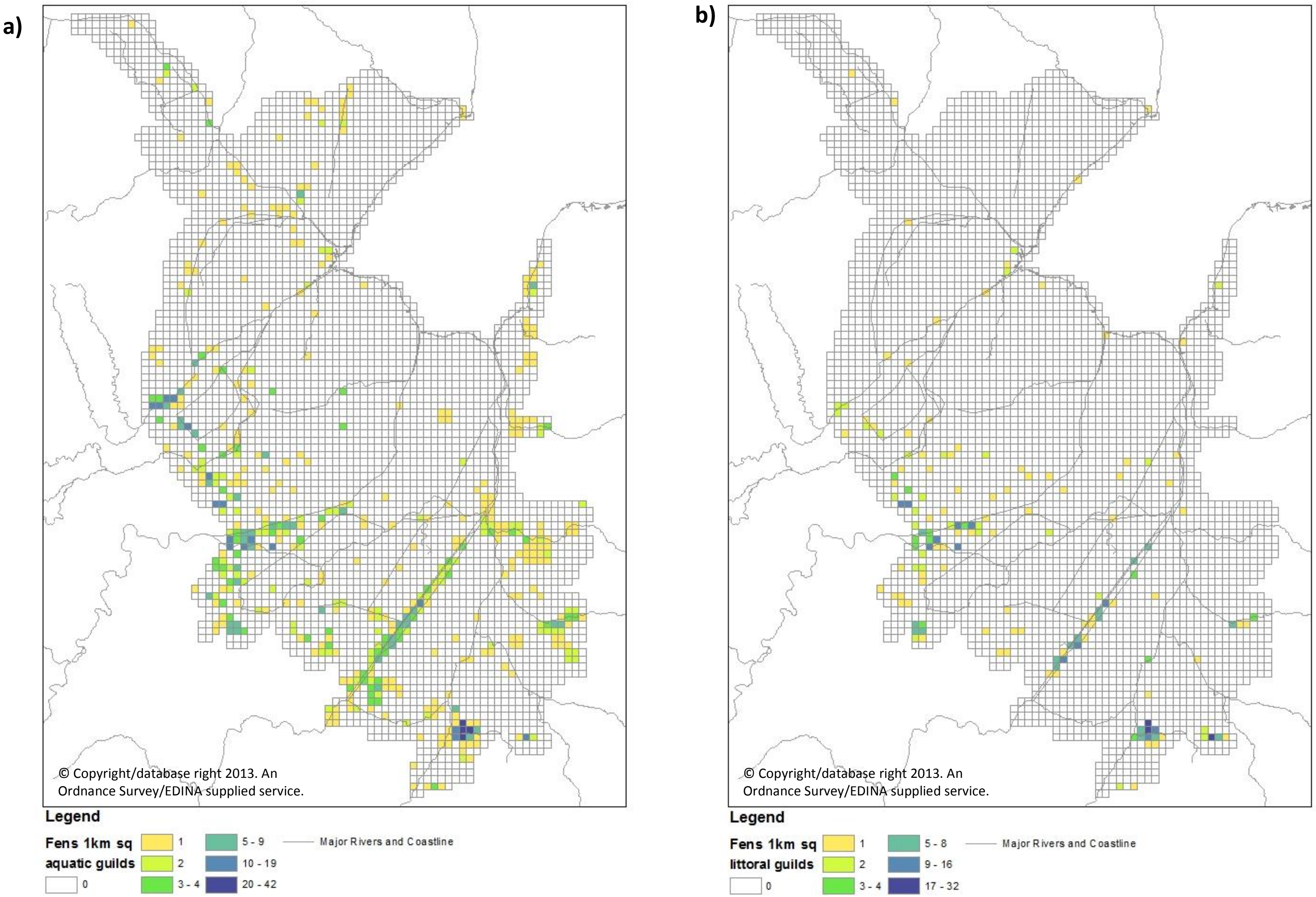


Fig. 3. Richness of species from a) aquatic management guilds and b) littoral management guilds, recorded in each 1 km square in the Fens NCA.

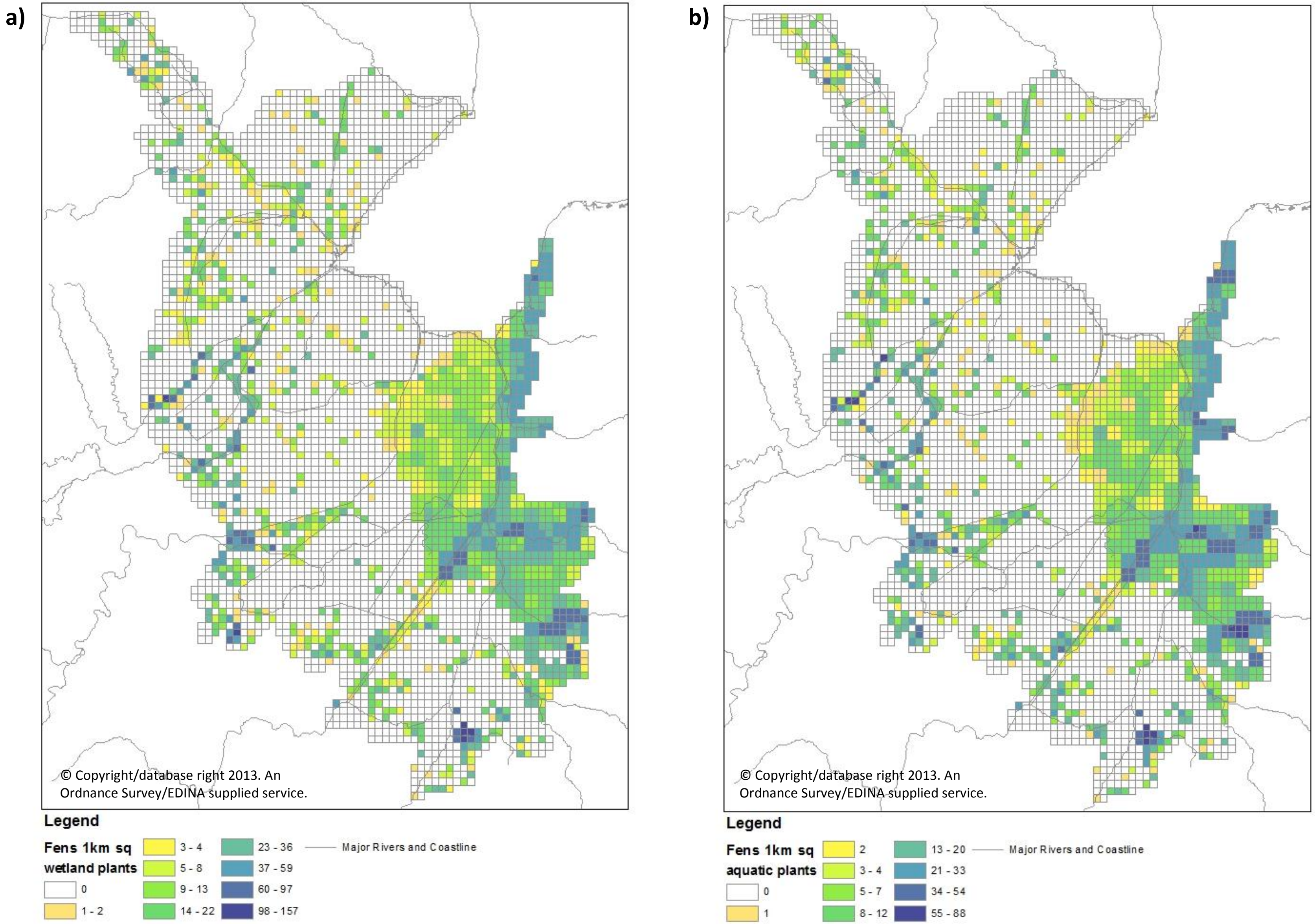


Fig. 4. Richness of a) wetland plant species, and b) aquatic plant species, recorded in each 1 km square in the Fens NCA.

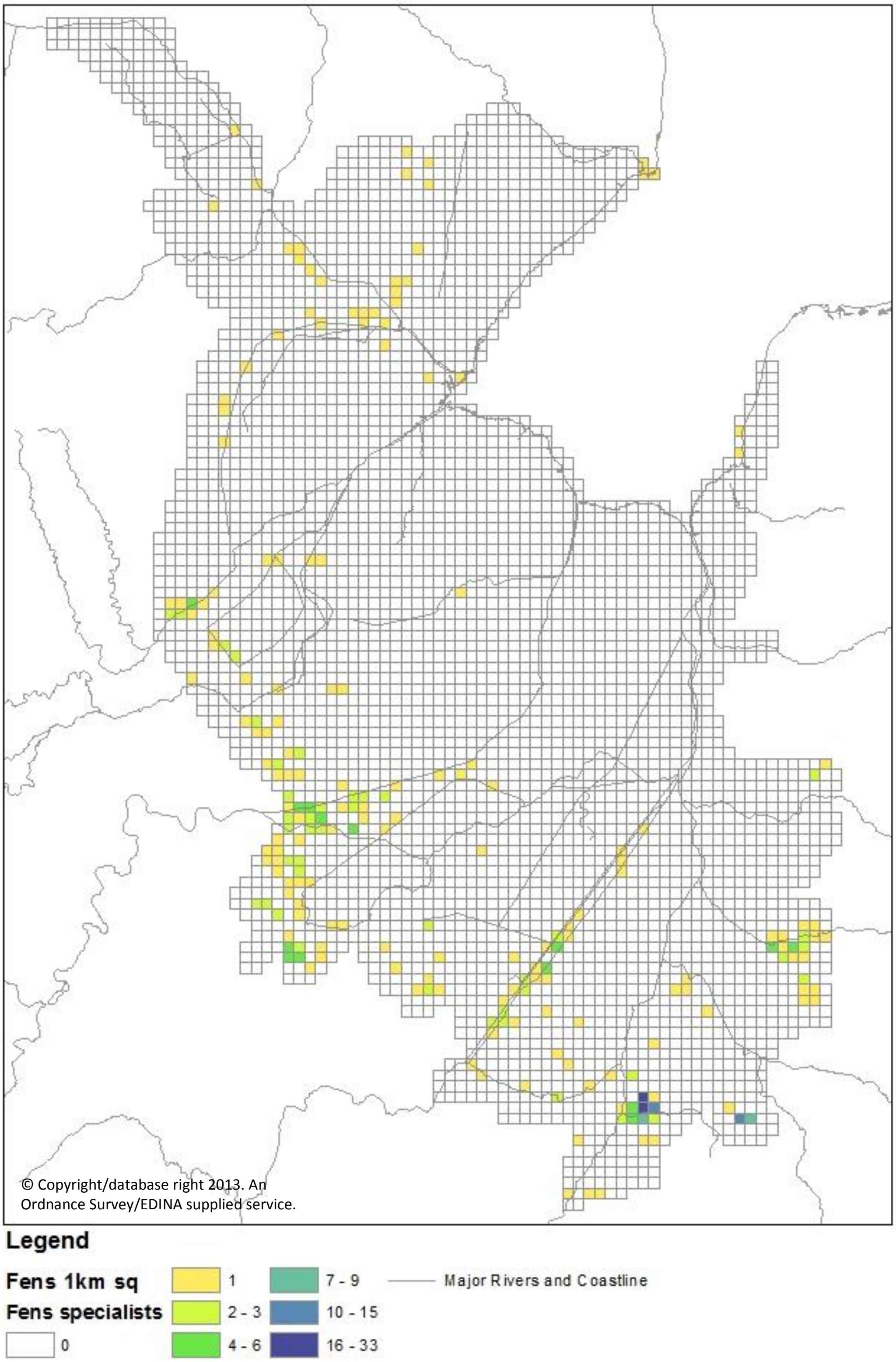


Fig. 5. Richness of Fen Specialist species recorded in each 1 km square in the Fens NCA.

Environmental predictors

The biodiversity of drainage channels in the Fens is determined by a combination of environmental factors, which may include ditch water quality, adjacent land-use, soil type, channel size, proximity to the edge of the Fen basin or to a Fen island, and proximity to upwelling groundwater.

Twenty-one environmental predictors were initially selected as candidates for modelling (Table 1). A single value of each variable was calculated for each 1 km square. Variables that considered “distance to” (e.g. distance to Fenland Island) were calculated from the centre of the 1 km square, while presence, aggregate length or percentage of area variables were calculated from the whole 1 km square.

We were unable to obtain suitably widespread or detailed data for water quality (including salinity) or the location of upwelling groundwater. We acknowledge that these are likely to be extremely important in determining the distribution of ditch biodiversity and suggest that such datasets are collated in the future. However, a number of modelled variables are likely to act as proxies for these effects (e.g. soil type, distance to main river, distance to tidal boundary).

The ecological value of the ditches, and therefore the richness and composition of species recorded from them, will also be affected by their physical management. However, information on factors such as ditch depth, profile and clearance frequency were not available. The details of Higher Level Stewardship (HLS) agreements at the individual farm scale may provide information regarding ditch management, but this is beyond the scope of this landscape-scale study. At a landscape-scale, the distribution and density of HLS agreements are rather uniform and as such would have little or no predictive power in the models; these were not therefore included in the models.

We obtained data regarding the Internal Drainage Board catchment identity (c.40 areas) but did not include this as an environmental predictor because the areas were considered to be administrative rather than ecological in nature, and were not thought to represent distinct hydrological catchments.

The potential importance of nitrate vulnerable zones (NVZ) was not examined in this study because the majority of the Fen basin (94% (Natural England 2013)) is classified as a NVZ, and as such would have little or no predictive power in the models.

The density (or aggregate length) of ditches within the 1 km square was considered to be an important predictor of network and biological quality. This was extracted from the *Surface_Water_Polyline* (Ordinance Survey: VectorMap District, 1:25,000) dataset. A number of geographic variables relating to drainage were extracted from Ordinance Survey data, including elevation, distance to the nearest fen island, and distance to the landward margin of the fen basin (Table 1, Fig. 6). Presence of, or distance to, major roads was also considered, as road/ditch banks may provide habitat features in their own right, and also as a proxy for access and potential recording bias. Further major groups of environmental predictors considered for modelling are considered below.

Land Cover and Land-use Intensity

Twenty-three land cover types are classified by the Land Cover Map (LCM 2007). Since the dominant land use in the Fens region is arable, we considered it potentially useful to distinguish between arable areas and those used for grazing, which was considered a potentially less intensive land use. LCM 2007 defines only one arable class (Arable and Horticulture) but several grassland types, including 'Improved Grassland' and 'Semi-natural Grasslands', which are further distinguished by LCM as Fen, Marsh and Swamp and Acid, Calcareous, Rough and Neutral Grasslands.

Fen, Marsh and Swamp was not considered to be a useful predictor because it only identified areas of known SSSI. While Acid and Calcareous Grassland types were extremely infrequent within the Fens and therefore not included. The two remaining categories of semi-natural grasslands were combined and the total area of Rough/Neutral Grassland within each 1 km square was calculated. Brief examination of such areas classified in the Fens as rough/neutral grassland suggests the classifications are meaningful, e.g. identifying Frampton marsh, the Ouse washes and large brownfield areas.

LCM 2007 classification of Improved Grassland is primarily based on its higher productivity (Morton et al. 2011). However, LCM 2007 acknowledge there may be confusion between improved grassland and arable fields (Morton et al. 2011). Improved grassland was therefore not included as a predictor.

Grades of the Agriculture Land Classification were considered as proxies for potential agricultural productivity, land-use intensity and therefore water quality. Grades 1 and 2 were considered to represent high intensity land-use, and Grades 3 and 4 relatively low intensities of farming. Grades 3 and 4 of the Agriculture Land Classification also overlapped with much of the area classified by LCM as improved grassland.

Sites of Special Scientific Interest

The aim of this analysis was to assess the distribution of wetland species across the drainage ditch network of the arable landscape. Wetland SSSIs are considered to be a reservoir of high quality biodiversity and therefore were excluded when modelling the distributions of species in the ditch network of the wider landscape. It was also important to identify 'wetland' SSSIs in order to calculate the distance to potential source populations of species. All biological SSSIs (excluding sites notified only for their geological features) within a 10km buffer of the Fens NCA were categorised as either sites comprising solely dry habitats or that contained any 'wet' habitats, whether open or wooded. Site classification was based on SSSI citation description (available at www.sssi.naturalengland.org.uk). Habitats considered to denote a 'wetland' SSSI included gravel pits, wet woodland or carr, fen, bog, grazing marsh and wet commons. SSSIs without wetland habitats were not considered since these are likely to be less important to the majority of ditch species.

Soil Classifications

Soil series and horizon data (NATMAP) were obtained under licence from the National Soil Resources Institute, Cranfield University. The Fens area includes a wide range of soil types, but is dominated by the division between peat and silt soils. However there are a number of peat soil types and so for the analysis, soil classifications were combined to obtain a one 'peat' and one 'silt' layer.

Silt was defined as the Cranfield soil classification, "Seasonally wet deep silty". Peat was defined following the report "Towards an assessment of the state of UK Peatlands" (JNCC 2011), that defined peat as comprising any of the following Cranfield NATMAP soil types; Peat; Seasonally wet deep peat to loam; Seasonally wet deep clay (marine alluvium and fen peat) and Seasonally wet deep sand (glaciofluvial drift and peat). The list of unit codes and extent of each within the Fens is provided in Appendix 4. Aggregating these different soil types into one combined "Peat" variable may miss important ecological differences and effects on ditch quality, but was considered preferable to modelling each separately, given their clumped distribution in the landscape, and the paucity of biological records that together indicate a simpler approach to modelling would be more robust.

Ditch Network Distance

The isolation of ditches from main channels and from tidal influence were considered potentially important determinants of water quality, saline influence and thus of biodiversity richness. We therefore calculated the shortest network distance along ditches and rivers from the centre of each 1 km square to the nearest main channel/river (Fig. 7a) and to the tidal boundary (Fig. 7b). These measures could be further enhanced if information on flow direction, speed, and volume (or cross-section area) were available.

Network distances were calculated in ArcGIS Spatial Analyst tools; this calculates the increasing distance from a defined source feature (e.g. the tidal boundary) along a network, such that near ditches have a low value and distant or isolated points have a high value. For the network distance to the nearest main channel/river the *River_Polyline* dataset (major, secondary and canals from Edina Digimap Ordinance Survey Strategi 1:250000) was used as the source. For the network distance to the tidal boundary the *Tidal_Boundary* data (VectorMap District High/Low Water Mark) was used as the source feature. The *Surface_Water_Polyline* (VectorMap District, 1:25,000) dataset was used as the ditch network feature.

Polylines were converted into a raster with 35 m cells. It was assumed that movement through all ditch sizes and types was equal. We then calculated a network distance, which assigned each of the 35 m cells in the network an incrementing value based on the shortest network distance to the feature of interest. A cell size of 35 m was selected in order to be large enough to connect any small breaks in the OS polylines, e.g. due to mapping error and underground drains, but small enough to prevent connection to ditches that were in close proximity but not thought be connected through surface water drainage. Some manual connections had to be imposed on the network due to large breaks in the mapped surface drainage or pumping stations. These were: an underground drain at North of Sutton bridge, R. Nene (TF487232); pumping station where Lower Knarr Fen flows into R. Nene at Knarr Cross Lake (TF345014); West Lynn, R. Ouse, sluice (TF611198); North Level Main Drain and R. Nene confluence where there are several sluices (TF466181); and The Haven and Maud Foster Drain confluence, Boston (TF334430) where several main roads cross the drain.

Occurrence of a county flora

There were substantial differences in the recording effort and coverage of plant species among counties. Counties with a comprehensive tetrad-based county flora (Norfolk and Suffolk) had good and uniform coverage of records. However, recording in remaining counties (Cambridge and Lincolnshire) was patchy, with many poorly or un-recorded squares contrasting with fewer exceptionally well-recorded squares. This division between the two groups of county was included as a binary covariate (0 = no flora, 1 = flora) when modelling the *plant-only* predictors.

Table 1. Environmental predictors calculated all 1 km square in the Fens Natural Character Area.

Environmental predictor	Source
Mean digital elevation: mean elevation of all 50 m x 50 m cells within the 1 km square (Fig. 6a)	Edina Digimap Ordinance Survey (OS) PANORAMA DTM (Digital Terrain Model) 1:50,000, 50m cells
Distance to Fenland "island": Fenland island defined as areas with an elevation of ≥ 5 m that were >0.1 km² in size (excluding coastal cliffs at Skegness and islands within large urban areas) (Fig. 6b). Several large 'islands' within 1000 m of the fenland basin were incorporated into the basin, i.e. not considered islands.	
Distance to Fenland "basin": basin was defined as the 5 m contour. However, see definition of fen island.	
Presence of either an A or B road within a square	OS Meridian 2 (composed of varying resolutions)
Distance to either an A or B road	
Distance to nearest "wet" SSSI – see below for definition	Natural England GIS Digital Boundary Datasets
Percentage of square comprising urban areas	Edina Digimap Ordinance Survey Strategic 1:250,000
Distance to nearest urban area	
Presence of a main river: including main rivers, secondary rivers and canals, but excluding minor rivers. The OS data classified the seaward c. 6 km of rivers as coast; the OS coast polyline was therefore merged with the river data.	
Network distance along "ditches" to the nearest "main river"/coastline: calculated using network cost distance (see above for full description). Main river as defined above. Ditch was defined using the VectorMap District *Surface_Water* polyline for accurate mapping of small ditches and open water, and the *Tidal_Boundary* (High/Low Water Mark) polyline because the surface water data stop at the tidal boundary.	
Network distance along ditch/river to the tidal boundary: calculated using network cost distance (see below for full description). Ditch/river defined using the Edina Digimap *River_polyline* and VectorMap District *Surface_Water* polyline. Tidal boundary was defined as the high water mark using the VectorMap District *Tidal_Boundary* polyline.	VectorMap District (1:25,000)
Index length of all ditches per 1 km square: ditches were defined as above. This is considered an index because polylines defined each bank of wide ditches or rivers, resulting in double-counting, as such the lengths are not accurate.	
Length of IDB managed drains/rivers	Natural England product supplied directly
Percentage of rough and neutral grassland	Land Cover Map 2007. Centre for Ecology and Hydrology
Percentage of grades of Agricultural Land Classification: percentage area of each of Grades 1-4.	Natural England GIS Digital Boundary Datasets
Percentage of peat soils: peat soil defined by JNCC (2011) as soil classes "Deep Peaty Soils/Peat"	NATMAP Cranfield University
Percentage of silty soils: silty soils defined as Cranfield Soil Class "Seasonally wet deep silty"	
Occurrence of a county flora: 0/1 if in a flora recorded county	

a)

b)

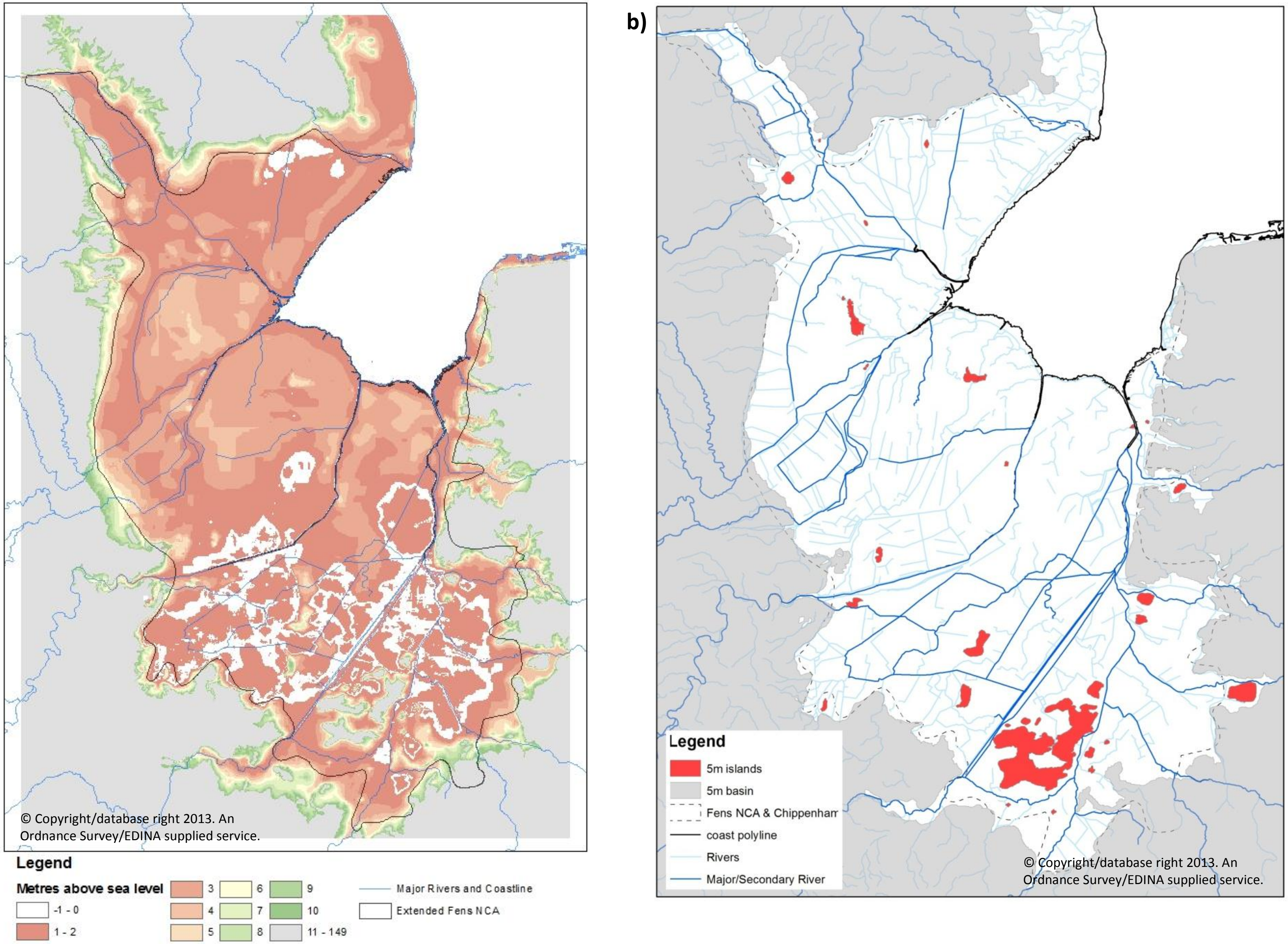


Fig. 6a) Land heights from Digital Elevation Models in the Fens NCA area and b) the areas defined as the Fen Basin and Fen Islands.

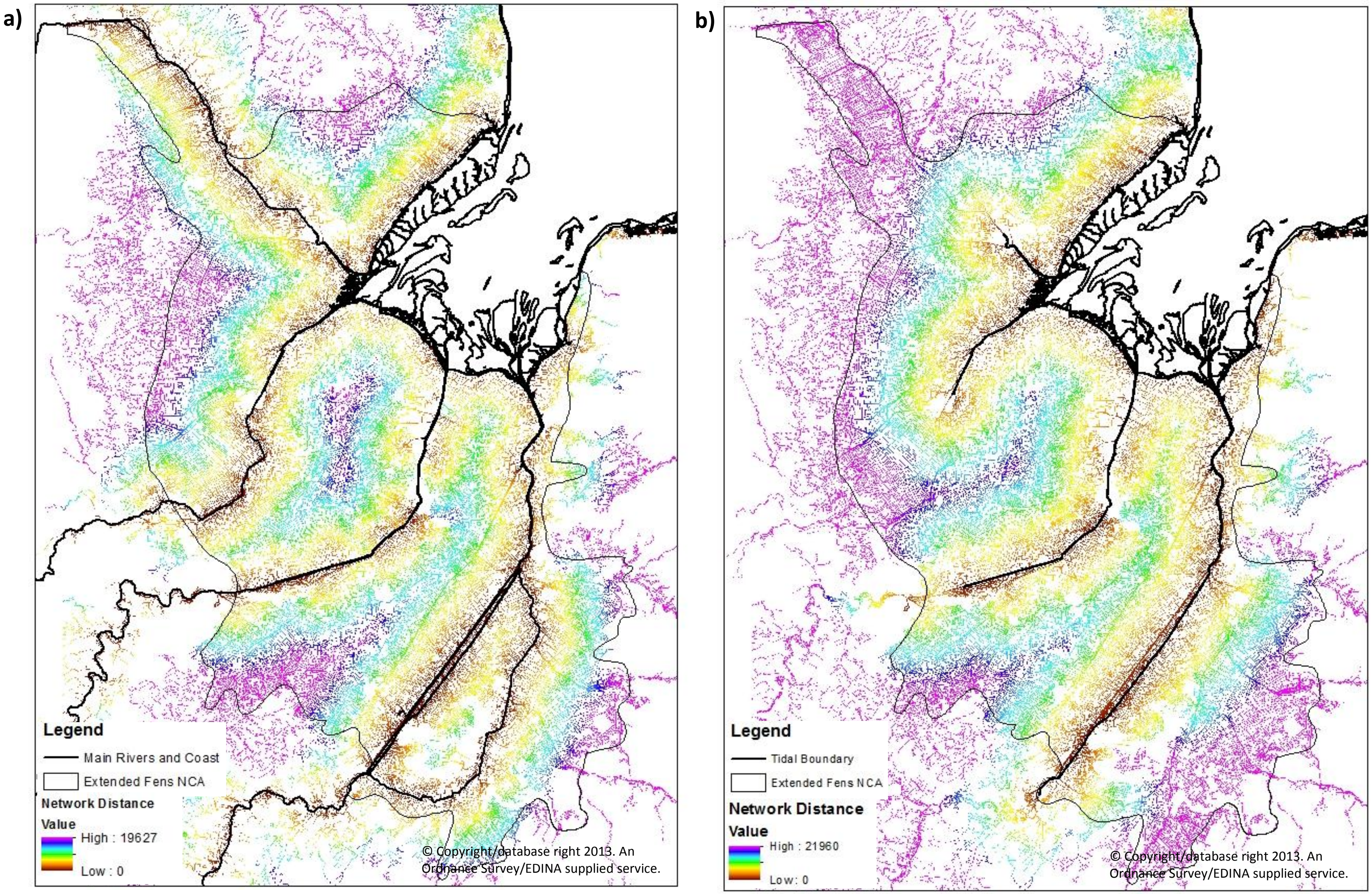


Fig. 7. Accumulating network distance along ditches from; a) main rivers, and b) the tidal boundary.

Selection of squares for modelling

Prior to modelling, a number of 1 km squares were excluded (Table 2). To ensure the study examined squares with appropriate conditions, we excluded squares without surface water. This included any surface water such as rivers, ditches, lakes and ponds (determined from the 1:25,000 Ordinance Survey). Some squares contained surface water that was isolated and not connected to the river network (i.e. were c. >70 m from next nearest surface water feature, created from a 35 m buffer). Network distances to a main river or the tidal boundary could not be calculated for these squares and they were excluded.

Squares whose area was >50% within the Wash SSSI were regarded as being highly saline influenced and were excluded. Squares wholly or partly comprising a wetland SSSI were also excluded (Fig. 8).

The distribution of excluded squares is given in Fig. 8.

Table 2. Criteria for the exclusion of squares in the modelling, and the number of squares that were excluded.

Selection principles for defining 1 km study squares	**No. of 1 km squares excluded**
Exclusion of squares with **no surface water** (defined by *Surface_Water polylines*)	50
Exclusion of squares **>50%** within the Wash SSSI	86
Exclusion of squares with any part (>0%) within a **wet SSSI**	216
Exclusion of any squares for which a **network distance** could not be calculated	50
Number of squares remaining (some squares excluded on multiple criteria)	3745

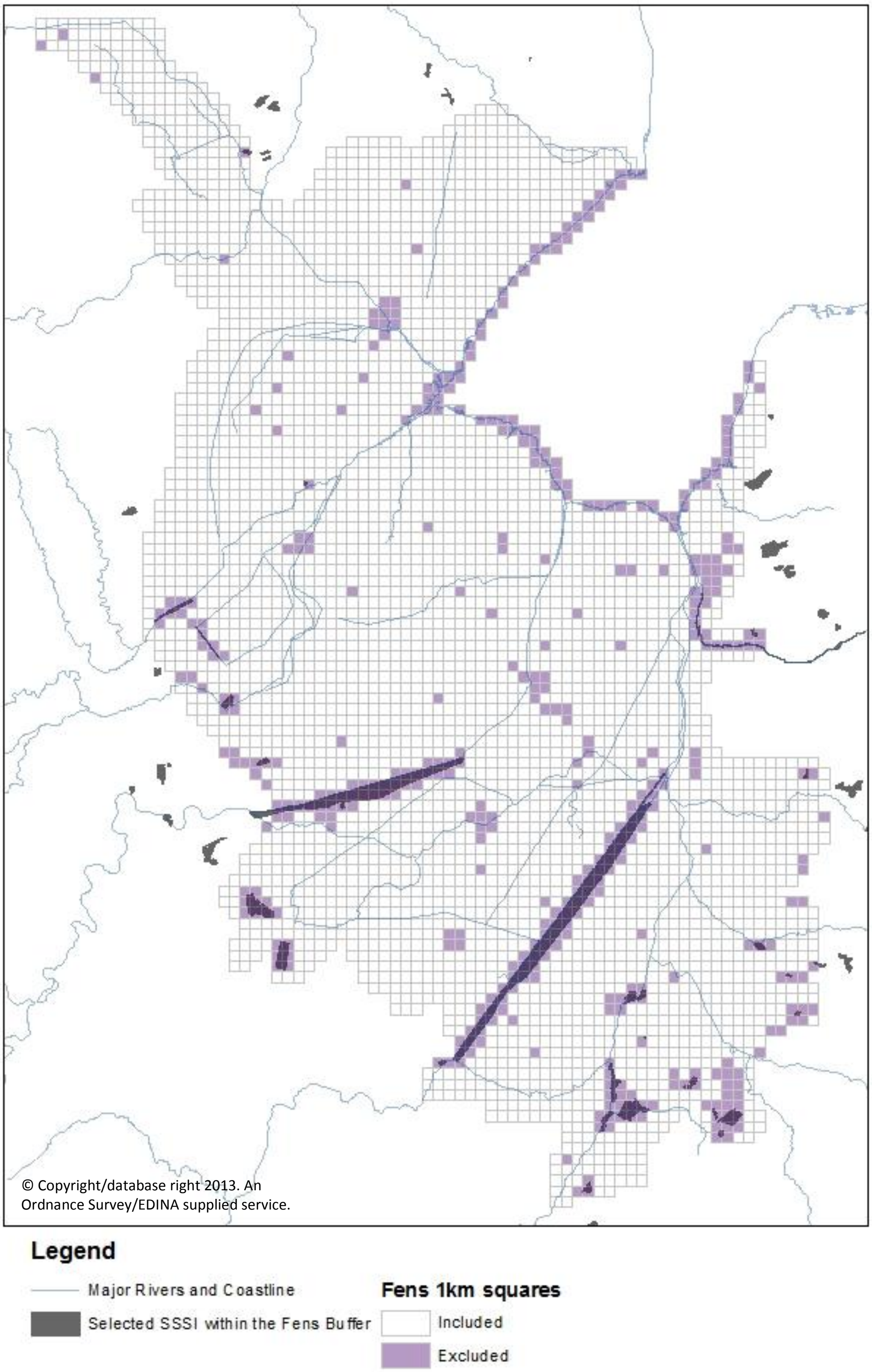


Fig. 8. Distribution of squares excluded from modelling (purple shading). Most squares were excluded because they were located wholly or partly in a SSSI that included wetland habitats (grey shading). Other reasons for exclusion are given above.

Modelling

Before proceeding with modelling, we first investigated if there was a significant correlation between urban areas and the number of records. It was hypothesised that levels of recording, particularly of Odonata, may be higher in urban areas due to submission of records from gardens. However, we found no correlation between Odonata richness (r=0.015, p=0.335) or the number of species of all wet guilds (r=0.004, p=0.800) per 1 km square and the percentage area of land cover that was urban. Urban areas were therefore not affecting recording effort and could therefore be considered as a candidate environmental variable to explain biological richness in the models.

Inter-correlations between predictor variables

Predictive models that contain variables that are highly correlated with each other can be unreliable, as it is difficult to accurately distinguish their individual effects. Therefore, inter-correlations between predictor variables were investigated using Pearson correlation coefficient and were considered to be large enough to potentially have an effect on the models if r >0.5, following Freckleton (2002).

Distance to nearest road and the presence of a road were negatively correlated (r=-0.627, Table 3). Presence of a road was selected in preference to the distance to the nearest road for inclusion in the models. Percentage urban land cover was highly negatively correlated with distance to an urban area (r=-0.505). The percentage of urban land cover was selected in preference for inclusion in the models. The presence of a main river was highly correlated with the network distance to a main river (r=-0.522). The network distance to a main river was selected in preference for inclusion in the models.

Distance to the Fen basin was strongly correlated with distance to the nearest wetland SSSI (r=0.533), network distance to the tidal boundary (r=-0.523), percentage of Grade 1 arable land (r=0.461) and percentage of silty soils (r=0.536). Distance to the Fen basin was therefore excluded from the modelling, whilst the other variables were retained.

The percentage of Grades 1 and 2 arable were strongly correlated with the percentage of silty soils (r=0.524 and r=-0.423 respectively). Grades 1 and 2 were therefore excluded from modelling. Grades 3 and 4 were combined into one variable that was not correlated with soil type (silt soils, r= -0.234; peat soils, r= -0.059) and was therefore retained for modelling.

The percentage of peat or of silt soils were not excessively correlated (r=-0.469). This is due to the presence of other soil types; almost 25% of 1 km squares contain no peat or silt soil types (Fig. 9). As peat and silt may have distinct and contrasting effects on biological quality, both were retained as candidate variables for models. The other dominant soil type was seasonally wet deep clay, which occurs predominately in the north-western edge of the Fens and in a band between the north-south division of silt and peat dominated soil types. Other soil types occurring in the Fens include loams, shallow clays, seasonally wet sandy soils and dry sandy or chalky soils.

The length of IDB drains was moderately correlated with the length of surface water (r=0.393). It was considered that the total length of surface water was more biologically meaningful than the length of IDB drain. The total length of surface water was therefore selected in preference for inclusion in the models.

Environmental predictors retained for consideration in models

- Mean digital elevation
- Distance to island
- Presence of A/B road
- Distance to nearest wetland SSSI
- Percentage of urban
- Minimum network distance to river
- Minimum network distance to tidal boundary
- Length of surface water (considered representative of ditch density)
- Percentage of rough/neutral grassland
- Total % silt soils
- % of peat soils
- % of grades 3 & 4 arable land – i.e. poor quality arable.
- Presence of a recent county flora (1/0 variable)

Table 3. Pearson correlation coefficients (r) between predictor environmental variables. Correlations between predictor variables were considered to be large enough to have an effect on the model if r>0.5.

	Mean digital elevation	Dist to Fen island	Dist to Fen basin	Presence of road	Dist to road	Dist to nearest wet SSSI	% urban	Dist to urban	Presence of main river	Network dist to main river	Network dist to tidal boundary	Length of surface water	Length of IDB drain	% rough/neutral grassland	% Grade 1	% Grade 2	% silt soil	% peat soil
Dist to Fen island	0.10																	
Dist to Fen basin	-0.19	-0.09																
Presence of road	0.16	-0.08	0.07															
Dist to road	-0.18	0.14	-0.01	-0.63														
Dist to nearest wet SSSI	-0.04	0.14	0.53	-0.04	0.10													
% urban	0.21	-0.02	0.05	0.32	-0.24	0.01												
Dist to urban	-0.30	0.02	-0.10	-0.32	0.38	-0.08	**-0.51**											
Presence of main river	-0.11	0.10	0.00	0.03	0.03	0.01	0.01	0.03										
Network dist to main river	0.18	-0.14	0.04	0.02	-0.10	0.04	0.07	-0.12	**-0.52**									
Network dist to tidal boundary	0.25	0.23	**-0.52**	-0.04	-0.06	-0.13	-0.06	0.07	0.00	0.00								
Length of surface water	-0.36	0.06	0.07	-0.02	-0.04	0.05	-0.18	0.03	0.14	-0.08	-0.03							
Length of IDB drain	-0.26	0.11	0.15	-0.05	0.03	0.19	-0.08	0.02	0.11	-0.07	-0.05	0.39						
% rough/neutral grassland	0.11	0.05	-0.11	0.04	-0.07	0.01	0.01	-0.10	0.08	-0.03	0.16	0.09	0.02					
% Grade 1	-0.24	-0.10	0.46	0.04	-0.04	0.15	-0.03	0.03	-0.01	-0.07	-0.38	0.12	0.07	-0.15				
% Grade 2	-0.04	0.10	-0.25	-0.10	0.13	0.00	-0.15	0.11	-0.03	0.05	0.26	0.07	0.09	0.06	-0.79			
% silt soil	-0.02	0.02	**0.54**	0.06	0.04	0.40	0.15	-0.22	0.05	-0.02	-0.45	-0.05	0.05	-0.05	0.52	-0.42		
% peat soil	-0.32	-0.12	-0.29	-0.09	0.10	-0.40	-0.20	0.32	0.02	-0.18	0.20	0.15	-0.03	-0.10	0.07	-0.01	-0.47	
Grades 3+4	0.45	0.01	-0.38	0.04	-0.10	-0.25	0.08	-0.16	0.02	0.06	0.25	-0.25	-0.23	0.15	-0.37	-0.22	-0.23	-0.06

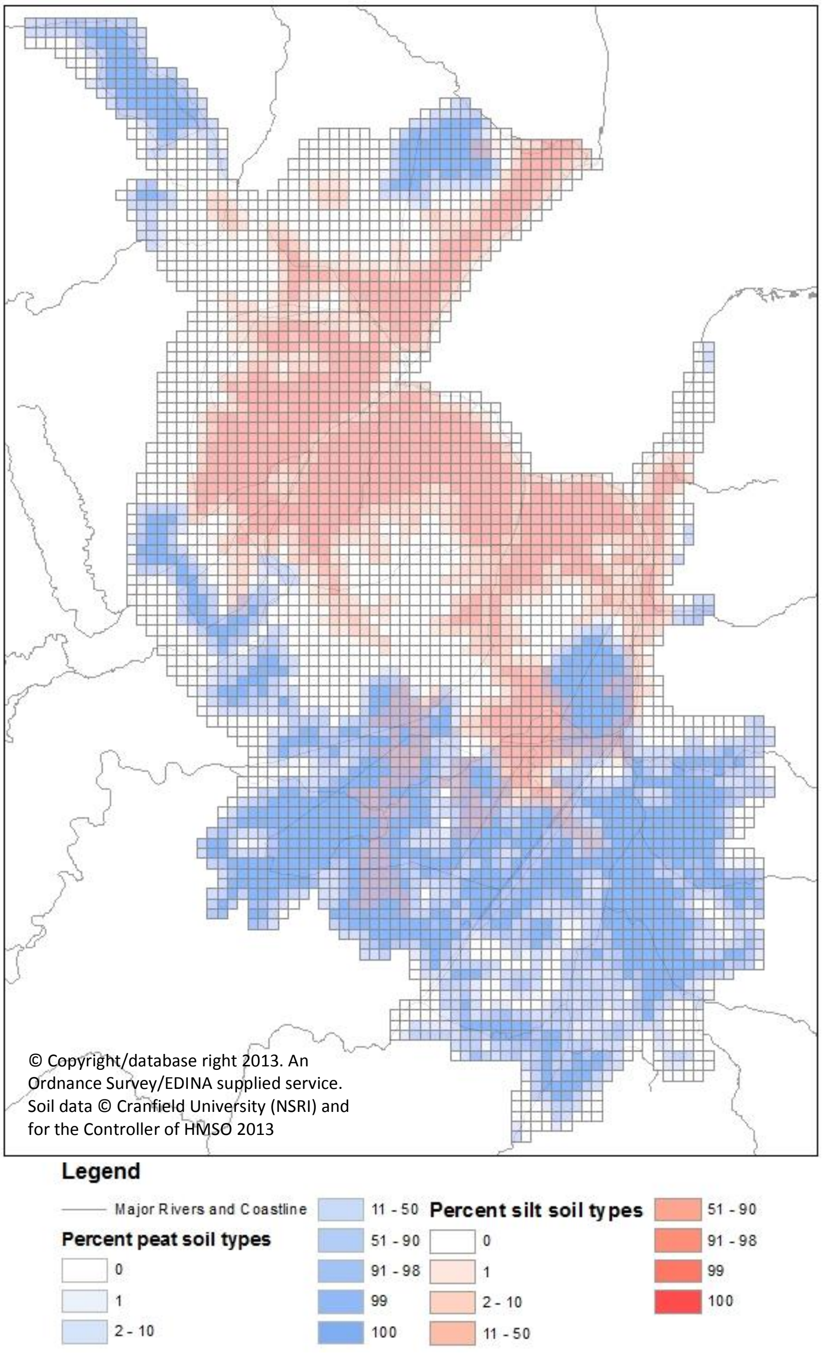


Fig. 9. Distribution of peat and silt soil types in the Fens NCA.

Model selection

Recording effort can differ among 1 km squares (median 41 records; range 0-50,567 records, 25% squares contained fewer than 5 records). This introduces noise or error into the available biological data. It is therefore desirable to control for recording effort in model construction.

A number of approaches were tested:

- excluding all squares with NO records;
- excluding all squares with <2 records;
- excluding all squares with <5 records (bottom 25%);
- weighting regression by transformation and standardisation of recording effort;
- explicitly including recording effort (total number of records per 1 km square, square-root transformed to reduce leverage) as a covariate.

The performance of these methods was assessed by training models on 75% of the data and testing on the remaining 25%, repeated for 100 different 75% samples of the data.

The best performing method was that incorporating recording effort (square-root transformed) as a covariate.

For each response variable, we fitted generalised linear models, with a quasi-poisson error structure to deal with over-dispersion, containing all predictor variables. In a backward elimination fashion, we removed non-significant variables from the model (assessing the significance of each parameter by examining the t-test of β estimates, with a threshold of $\alpha<0.05$) until we were left with a minimum adequate model containing only significant variables.

Predicting richness of ditch biodiversity

Our aim was to predict the quality of the ditch network, having accounted for differences in recording effort. If the number of records made for a particular square were included in the predictive model along with the values of the environmental variables, then those squares with fewer observations would be predicted to have fewer species. We therefore predicted the 'true' richness opposed to observed richness, after standardising recording effort, by setting the number of records in each 1 km square to be the overall median (41 records) and used the minimum adequate models to predict the values of the response variables. In the same way, we standardised for the presence of a recent flora, by setting the value for all squares as 1.

Note: In some squares, predicted species richness may be lower than recorded species richness because the models capture variation in *relative* species richness, but are poorer at capturing absolute values, particularly at the extremes.

Effects of the environment and location on biodiversity richness

Overall, the models explained 24-47% of the variation in species richness. Surprisingly, recording effort (number of records) accounted for only 1-8% of the variation in richness.

The effects of many environmental predictors were consistent between species groups (Table 4). Mean elevation above sea level was not a significant predictor of the richness of any species groups (Fig. 10). A high percentage of silty soils had significant negative effects on all groups. Generally however, the distribution of peat soils was not an important determinant of species richness (Fig. 10). There is small-scale heterogeneity of soil type within ditches, such areas of silty ditches in peat dominated areas. Whilst this is likely to have important effects on the distribution of biodiversity, there is insufficient data available regarding the spatial distribution of such small-scale heterogeneity to include it in the model.

Richness of all groups was significantly greater closer to existing wetland SSSIs. Whilst there may be a tendency for greater recording effort closer to SSSIs, recording effort was included in the model as a covariate and so much of this has been accounted for. Species richness may be greater closer to wetland SSSIs because such sites act as reservoirs of wetland species or because conditions not included in the models (e.g. water quality) are better closer to those SSSIs.

The richness of most groups increased significantly with increasing length of surface water (an index of ditch density) and, excepting littoral species and Fen Specialists, with increasing percentage of Grade 3 & 4 agricultural land (i.e. with lower land-use intensity).

Minimum network distance to the tidal boundary had a significant effect on all groups, with the exception of the richness of species from all wetland guilds. The richness of Odonata and Fens Specialists increased further from the tidal boundary. In contrast, the richness of remaining groups (aquatic and littoral guild, and wetland and aquatic plants) was higher in squares closer to the tidal boundary. This is an important contrast, such that network planning must either take a mixed approach, or prioritise Fens Specialists versus remaining groups.

Odonata richness
The minimum adequate model explained 29.9% of the variation in Odonata richness, with 1.3% of the variation accounted for by recording effort. Odonata richness was greatest in 1 km squares closer to Fen islands and wetland SSSIs, and in squares with peaty rather than silty soils (Fig. 10). Odonata richness was also greatest in squares that included a main river (Fig. 11a). Odonata richness also increased with distance from the tidal boundary.

Richness of conservation priority species from littoral guilds
The minimum adequate model explained 27.3% of the variation in littoral guild species richness, with 7.7% of the variation accounted for by recording effort. Littoral species richness was greatest in 1 km squares closer to wetland SSSIs, particularly the Ouse and Nene Washes (Fig. 11b), and closer to the tidal boundary. Littoral species richness was

greatest in squares dominated by neither peaty nor silty soils (with a negative effect of both of these soil types, Fig. 10).

Richness of conservation priority species from aquatic guilds

The minimum adequate model explained 26.7% of the variation in aquatic guild species richness, with 3.7% of the variation accounted for by recording effort. The richness of aquatic species was greatest in 1 km squares closer to wetland SSSIs and the tidal boundary, and with high length of surface water. The presence of a main river also had a positive effect on species richness (Fig. 12a). A high percentage of silty soils had a significant negative effect on the richness of aquatic species (Fig. 10).

Aquatic plant species richness

The minimum adequate model explained 47.0% of the variation in aquatic plant species richness, with 1.0% of the variation accounted for by recording effort. Unsurprisingly, aquatic plant richness was much higher in squares in counties that had been the subject of a recent Flora project (Fig. 10). Richness increased in squares closer to wetland SSSIs, Fen islands and the tidal boundary (Fig. 12b).

Richness of species from wetland guilds

The minimum adequate model explained 33.0% of the variation in wetland guild species richness, with 3.0% of the variation accounted for by recording effort. The richness of wetland species was greatest in 1 km squares closer to wetland SSSIs and Fen islands, and those with greater length of surface water. The presence of a main river also had a positive effect on species richness (Fig. 13a). A high percentage of silty soils had a significant negative effect on the richness of wetland species (Fig. 10).

Wetland plant species richness

The minimum adequate model explained 49.3% of the variation in wetland plant species richness, with 1.4% of the variation accounted for by recording effort. As expected, wetland plant richness was much higher in squares in counties that had been the subject of a recent Flora project (Fig. 10). Wetland plant richness increased in squares closer to wetland SSSIs and to the tidal boundary (Fig. 13b).

Richness of Fen Specialist species

The minimum adequate model explained 24.1% of the variation in Fens Specialist species richness, with 5.2% of the variation accounted for by recording effort. The richness of Fens Specialists was greatest in 1 km squares closer to wetland SSSIs and Fen islands, further from the tidal boundary (Fig. 14) and those with high length of surface water. Richness of Fen Specialists was greatest in Lincolnshire and Cambridgeshire, compared to Norfolk and Suffolk (i.e. counties without a recent flora). A high percentage of silty soils had a significant negative effect on the richness of Specialist species (Fig. 10).

Table 4. Summary of the direction and the magnitude of the effects of environmental predictor variables on the richness of ditch indicator groups. Only significant ($p<0.05$) effects are shown.

	Odonata	**Fen specialist**	**Aquatic guild**	**Littoral guild**	**Wetland guild**	**Aquatic plant**	**Wetland plants**
% of grades 3 & 4	↑				↑	↑	↑
% of peat soils	↑↑			↓↓			
% of silt soils	↓↓	↓↓	↓↓	↓↓↓	↓↓	↓	↓
% of rough grassland	↓						
Length of surface water	↑	↑↑	↑↑	↑↑↑	↑↑↑	↑↑	↑
Proximity to tidal boundary	↓	↓	↑	↑↑		↑	↑
Proximity to main river	↑↑		↑		↑		
Proximity to wetland SSSI	↑↑↑	↑	↑↑	↑↑↑	↑↑↑	↑↑	↑↑
Proximity to fenland island	↑↑	↑↑		↑	↑	↑	

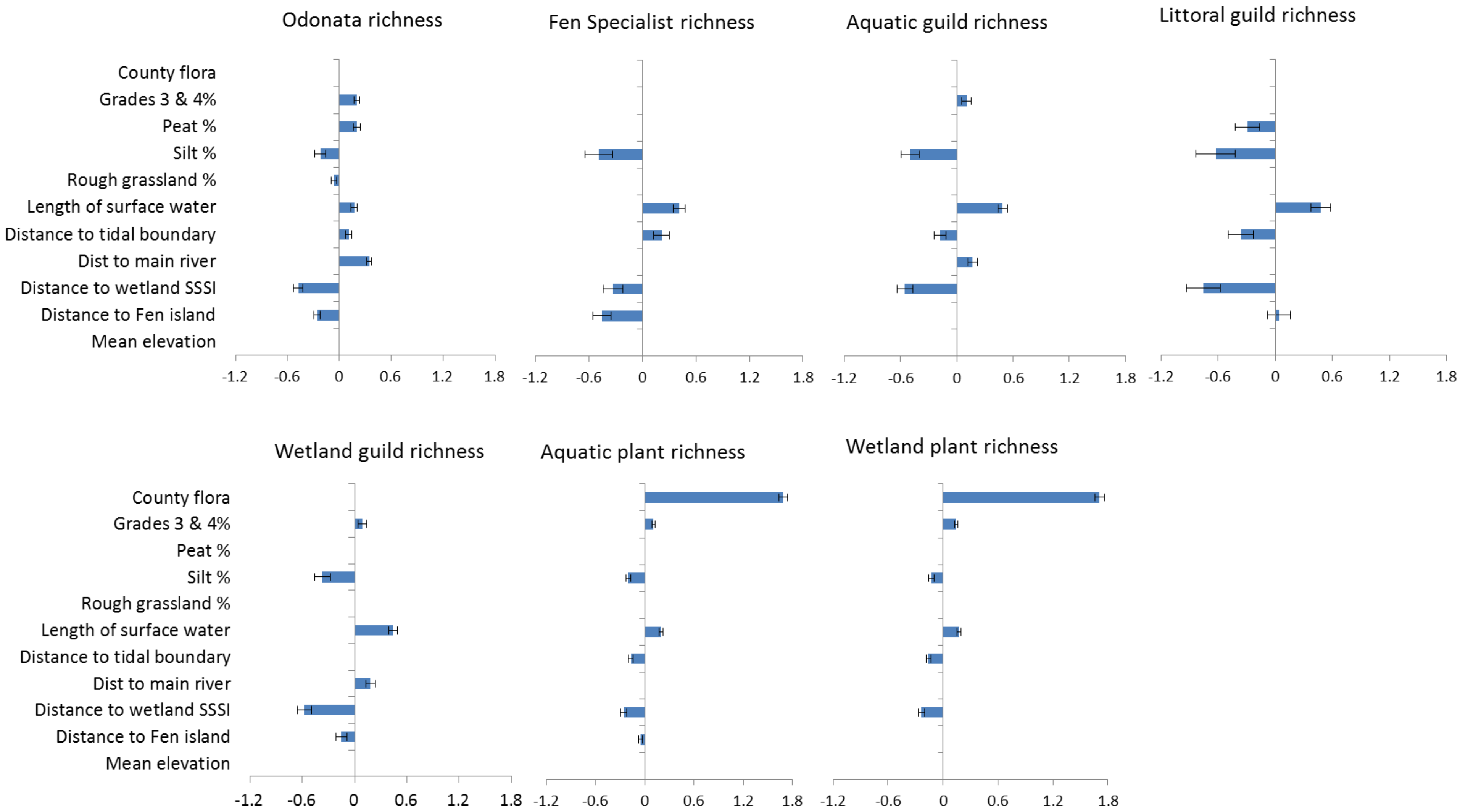


Fig. 10. Mean (±) magnitude of the effects of environmental predictor variables (β values) on the richness of ditch indicator groups. Only significant ($p<0.05$) effects are shown. All environmental variables were standardised so that the magnitude of the effects are comparable.

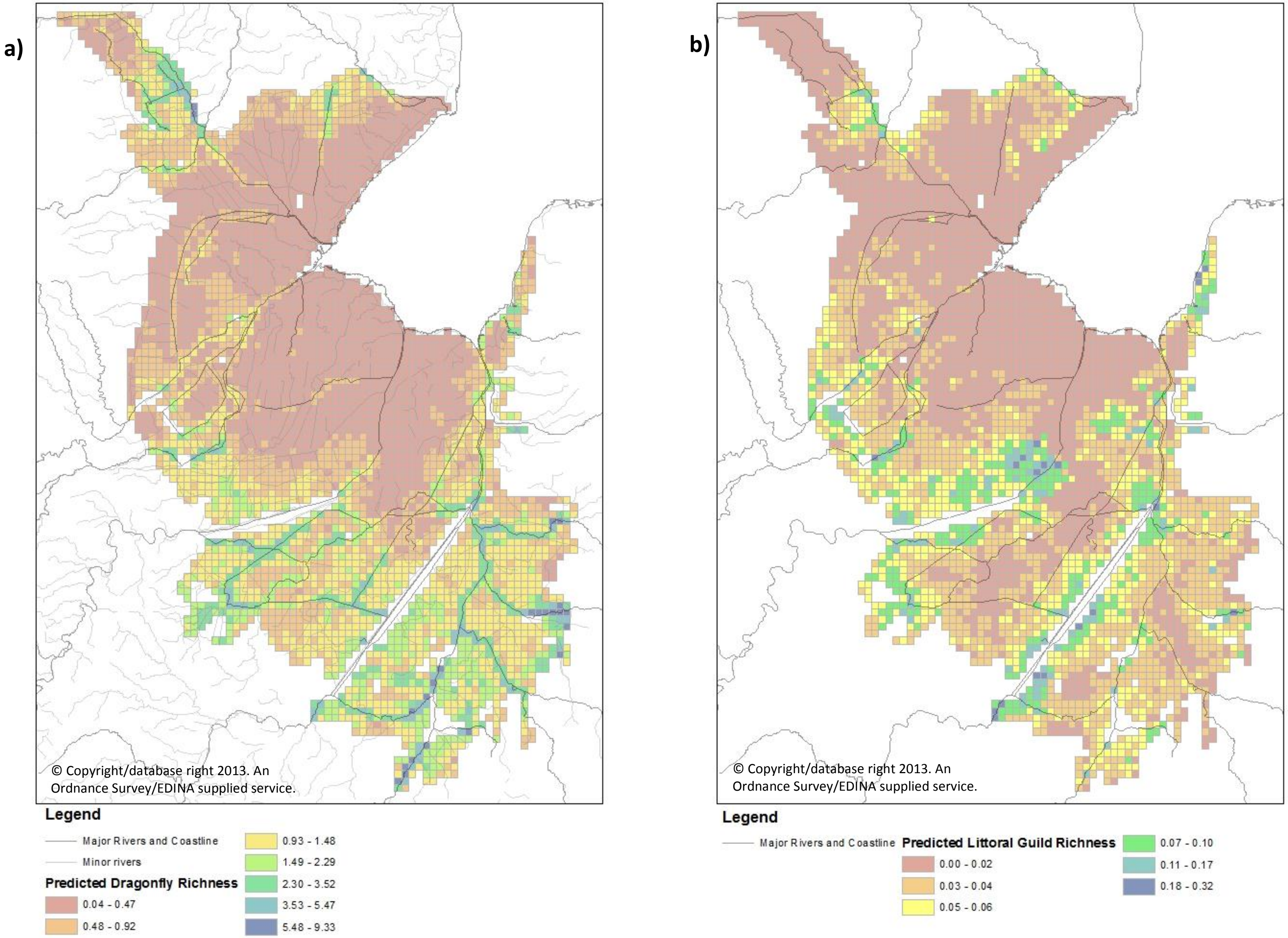
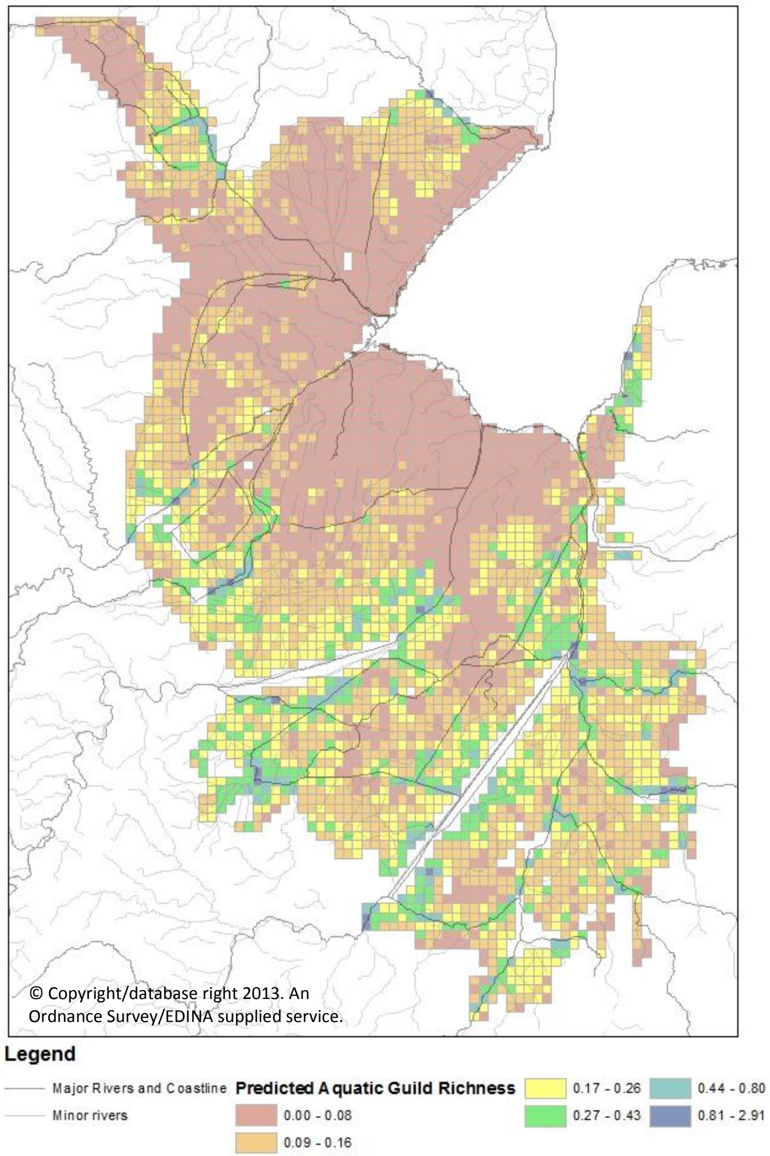


Fig. 11. Predicted richness per 1 km square based on models for a) Odonata species, and b) species from littoral guilds. White areas denote 1 km squares that were excluded (see above for reasons for exclusion).

a)



b)

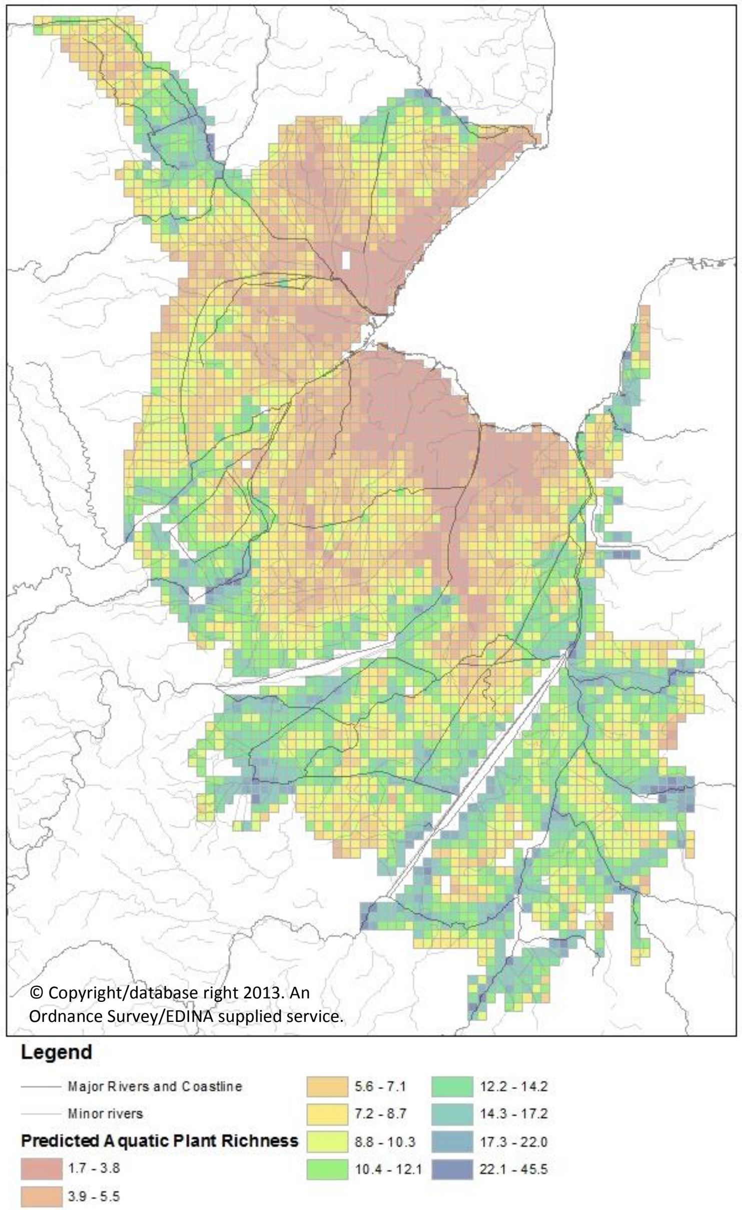


Fig. 12. Predicted richness per 1 km square based on models for a) species from aquatic guilds, and b) aquatic plant species. White areas denote 1 km squares that were excluded (see above for reasons for exclusion).

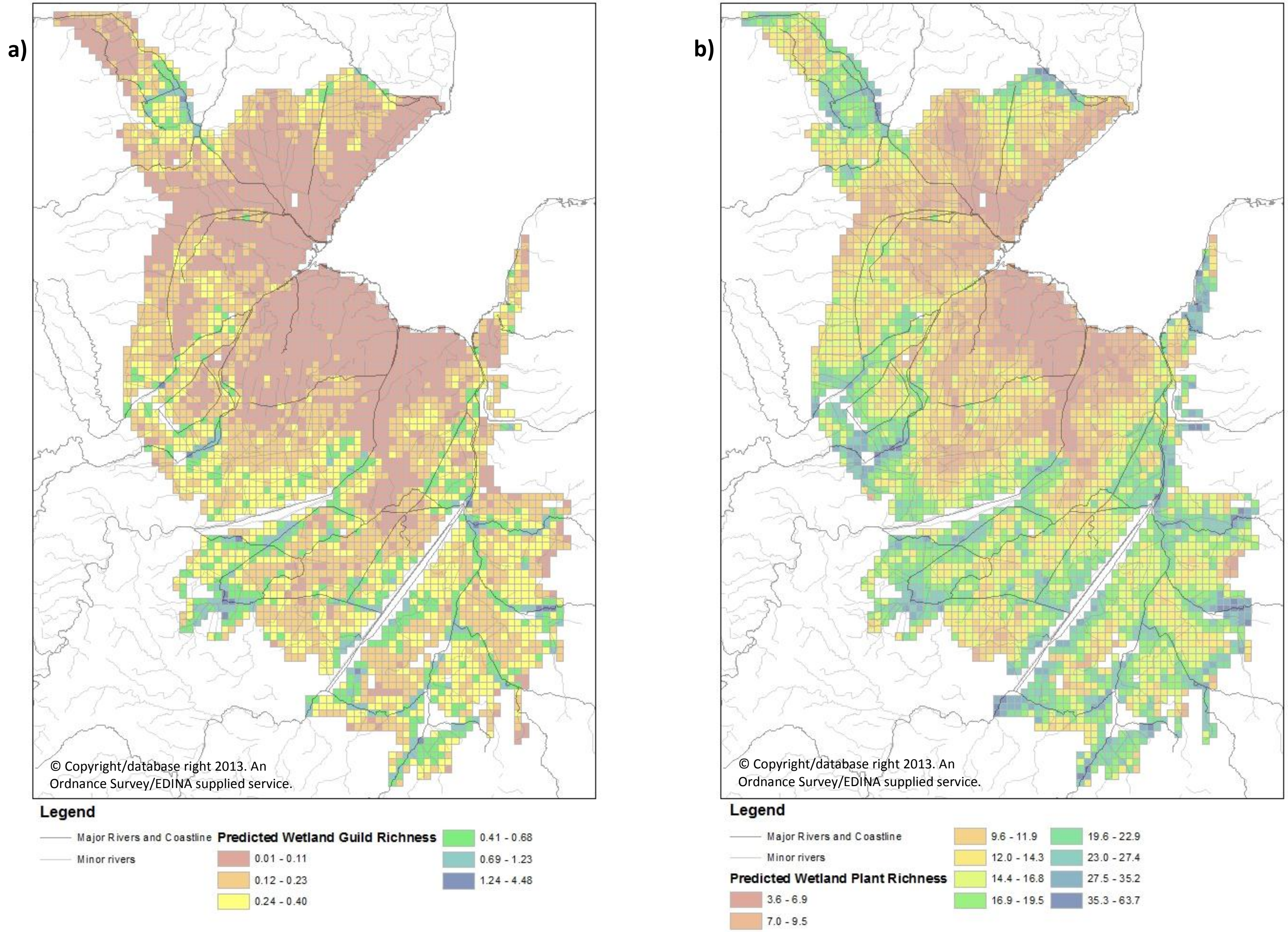


Fig. 13. Predicted richness per 1 km square based on models for a) species from wetland guilds, and b) wetland plant species. White areas denote 1 km squares that were excluded (see above for reasons for exclusion).

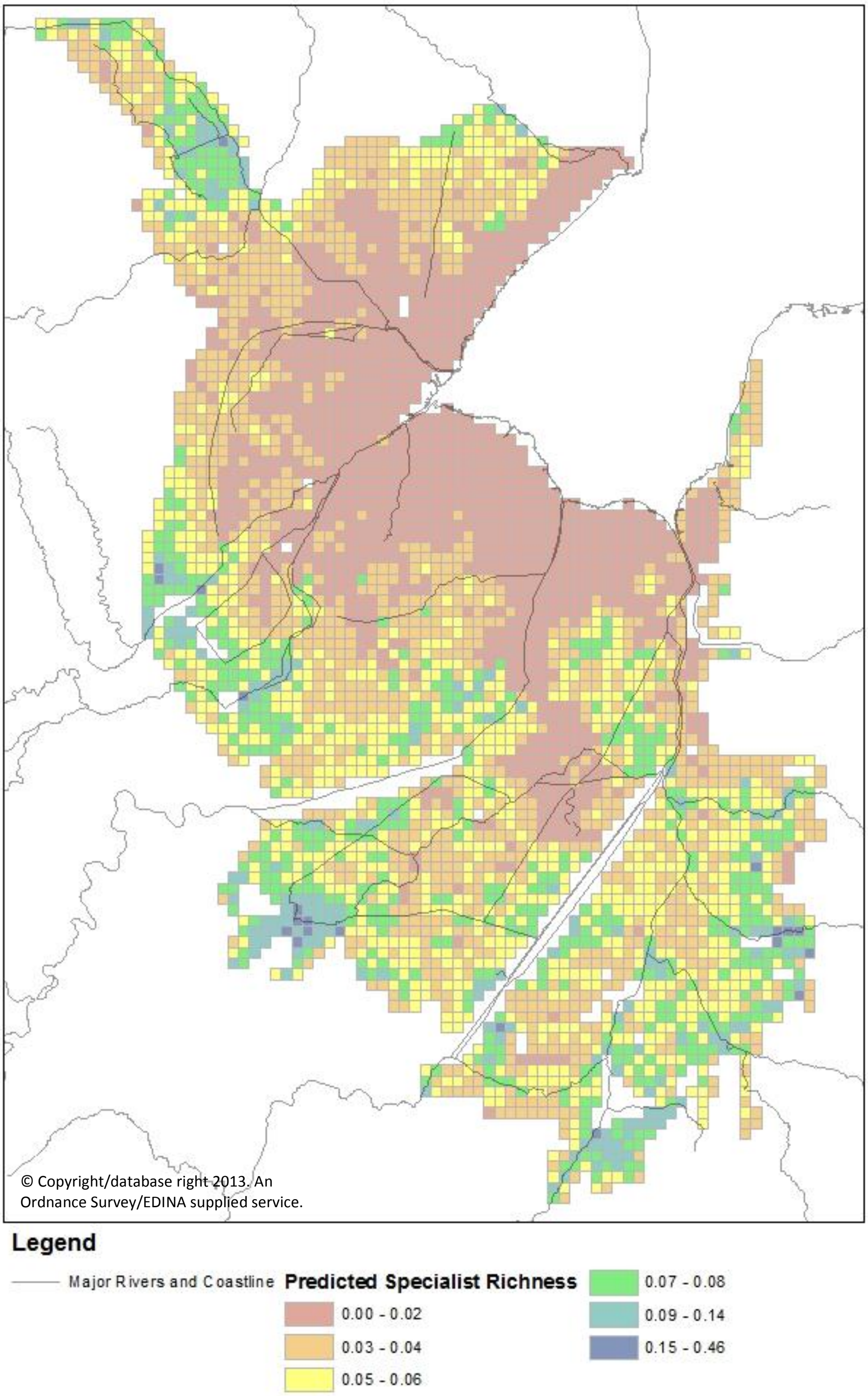


Fig. 14. Predicted richness of Fens Specialist species per 1 km square based on models. White areas denote 1 km squares that were excluded (see above for reasons for exclusion).

Biodiversity potential of the proposed network corridors

The predicted distributions of most species groups are similar, with species richness highest nearest the major rivers. However, the predicted distributions of littoral guilds and Fens Specialists are located in more isolated hotspots in the landscape, with the Ouse and Nene Washes not connected by areas of high predicted biodiversity (Figs. 11b & 14).

The predicted richness of ditch biodiversity indicators is low around the Wash (Fig. 15), particularly in the highly productive arable areas on silty soils. However, species richness was high in a many areas of high intensity Grade 1 arable land, as the region is predominately this grade. Overall, river channels had high biodiversity richness, with a number of species groups being positively influenced by the presence of a main river (Fig. 10). However, their value generally decreased when located in silty soils or if located further from a wetland SSSI (Fig. 15).

A network of proposed corridors have been suggested by the Fens for the Future "A Strategic Plan for Fenland: A Proposal for an Enhanced Ecological Network" (Keymer and Brayshaw 2012).

There are two potential strategies for the placement of new connectivity and habitat improvements. Conservation action could either be targeted towards connecting and managing areas of current high predicted biodiversity. This would increase resilience by allowing movement of species through areas of high biodiversity value and by increasing the overall size of such areas. Alternatively, conservation spend could be targeted towards improving areas currently of low biodiversity and linking these to areas of high value, which could act as sources for colonisation into the poorer areas. In the short term, this may increase the wetland biodiversity of the poorer areas. However, the most specialist wetland species, those most likely to be of the highest conservation priority, are likely to be more specialist in their requirements and poorer areas of the landscape may be unsuitable for them, rather than just isolated. We have assumed the first strategy when comparing the current proposed landscape connectivity network to our predicted areas of biodiversity richness.

Predicted richness of ditch species suggests that the currently proposed network corridors are generally well placed (Figs. 15, 16 & 17). This may in part be due to the focus on main rivers and drains. The proposed priority corridors are largely (>75% of corridor length) located in areas of the highest predicted biodiversity richness (Fig. 16). In contrast, approximately 25% of the length of proposed secondary corridors is located in areas of the lower predicted biodiversity value (Fig. 16).

The proposed priority corridor aims to join the three areas of the Great Fen, Ouse Washes and Nene Washes. Comparison of this proposed corridor and predicted biodiversity values suggests the corridor passes though some areas of lower biodiversity (e.g. White Fen and Flood Ferry). There may be some added biodiversity benefit from connecting areas further downstream, e.g. near March. However, this is logistically more difficult since it would involve making landscape corridors through more minor ditches.

In the north of the Fens NCA, proposed landscape corridors currently follow the main rivers of the Witham and West Fen Catchwater Drain/Stone Bridge Drain to their confluence at Boston (Fig. 17, A). These drains pass through areas of low predicted biodiversity richness. There may be improved biodiversity benefit from focussing on the northern end of the Catchwater Drain and creating a corridor running east to west along the northern edge of the Fens basin. This would help connect the River Witham and the high predicted biodiversity areas in Stickney and The Deeps regions, which is currently isolated in a small catchment (Fig. 17, B).

Improving connectivity using the South Forty Foot Drain, as currently proposed, appears to be the only feasible way of connecting the South Lincolnshire Fens to the River Witham. However, some minor alterations based on the predicted biodiversity richness may be beneficial; for example increasing connectivity to the north of Boston, e.g. through Sutterton Fen (Fig. 17, C). A corridor from the River Glen at Surfleet, through Gosberton Fen and Quadring High Fen, to join the South Forty Foot Drain near Donington would connect areas of high biodiversity value (Fig. 17, D).

Another potential area for improved connectivity would link high biodiversity value ditches around the Ouse Washes, such as Fodder Fen, to the River Great Ouse (Fig. 17, E). It may also be possible to link Chettisham Meadows in this way. Whilst the predominant habitat of Chettisham Meadows is dry grassland, the interface between quality dry and wetland habitat is now rare and there may be significant biodiversity benefits in improving this, using the adjacent ditches.

Although the Fens for the Future project mapped potential priority and secondary corridors, no assessment had been made of the most effective location of buffer areas or stepping stones. The map of predicted biological value shows considerable variation in the biological quality of the ditch network across the wider agricultural countryside. These maps can be used to support cost-effective targeting of interventions to improve ditch management and biological value, including agri-environmental measures.

Conclusions

The effects of many environmental predictors were remarkably consistent between species groups. Biodiversity richness was lowest in the areas of silty soils. Whilst silt soil *per se* may have an important effect on ditch species, silty soils were highly positively correlated with the percentage of Grade 1 arable land. From this analysis, it is not possible to separate the direct effects of soil type from indirect effects of agricultural land-use intensity. The percentage of peat soils was not an important determinant of species richness.

Interestingly, the distance from the tidal boundary had contrasting effects on different species groups. There may be other environmental factors, not included in this study, which are correlated with distance from tidal boundary, such as water quality.

Biodiversity richness was greater closer to existing wetland SSSIs. This may be because the high quality SSSI sites are acting as reservoirs of wetland species. However, there may be other conditions, not included in this study (e.g. water quality), which are highly correlated with the distance to the SSSIs. Nevertheless, this supports a strategy of buffering and extending the area of existing remnants of fen.

Overall, the connectivity network proposed by Fens for the Future largely concurs with areas of high predicted biodiversity value (Fig. 17). Assuming that conservation spend is targeted towards connecting and managing areas of current high predicted biodiversity, the current proposed network provides a good basis for targeting connectivity and habitat improvements. The maps of predicted biodiversity richness highlight other areas of current high biodiversity value that should be considered for the strategic targeting for agri-environment measures and other means to enhance ditch management. Targeting conservation effort towards improving those areas of high predicted biodiversity value may provide higher conservation value to the most specialist wetland species than connecting poorer quality areas.

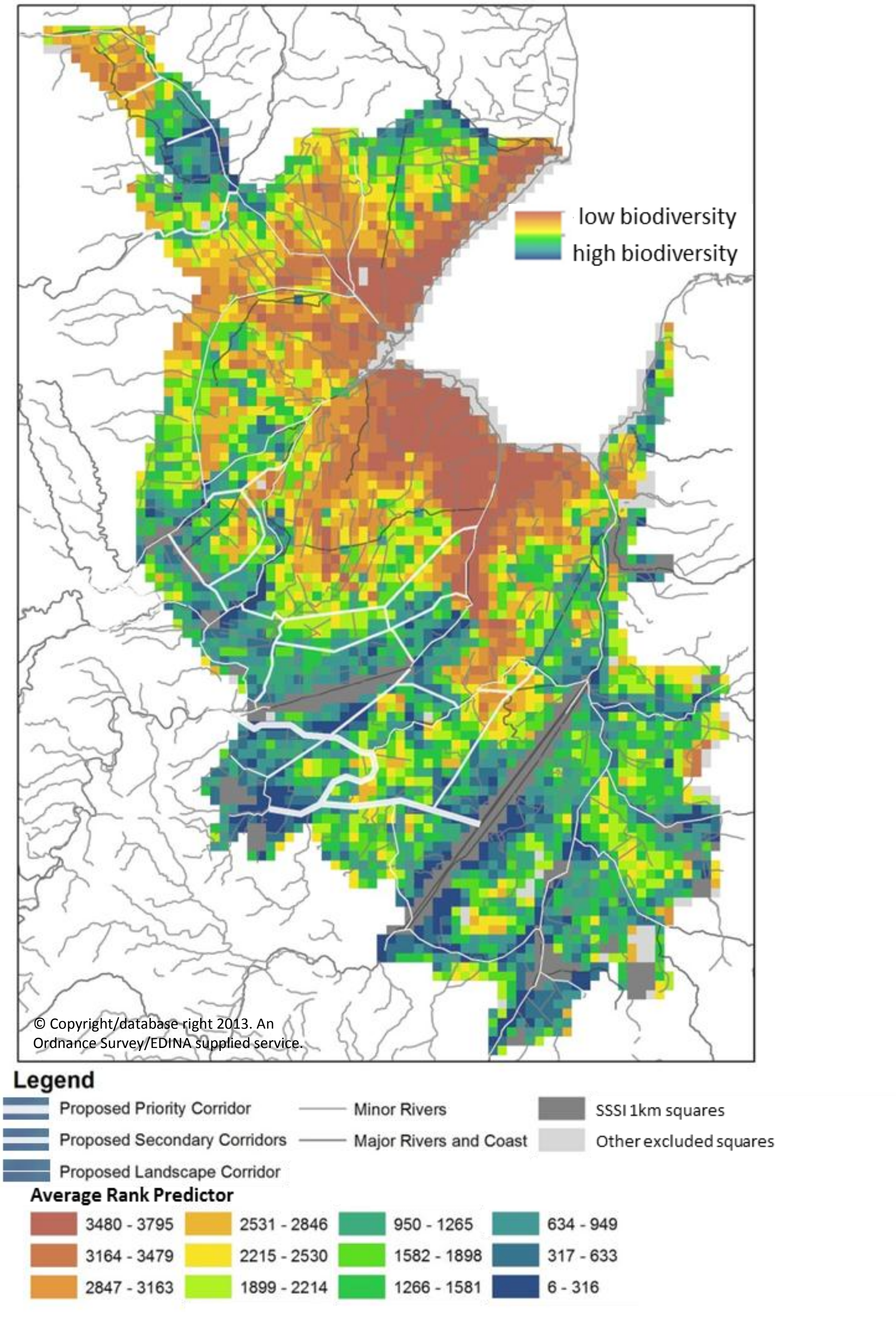


Fig. 15. The mean of the ranked predicted values for the seven biological response variables of each 1 km square. Main rivers and the existing proposed corridors (excluding the Landscape Corridor) are also shown. Brown colours (low rank) indicate squares with low predicted biodiversity and blue colours (high rank) to areas with high biodiversity. White lines denote proposed corridors.

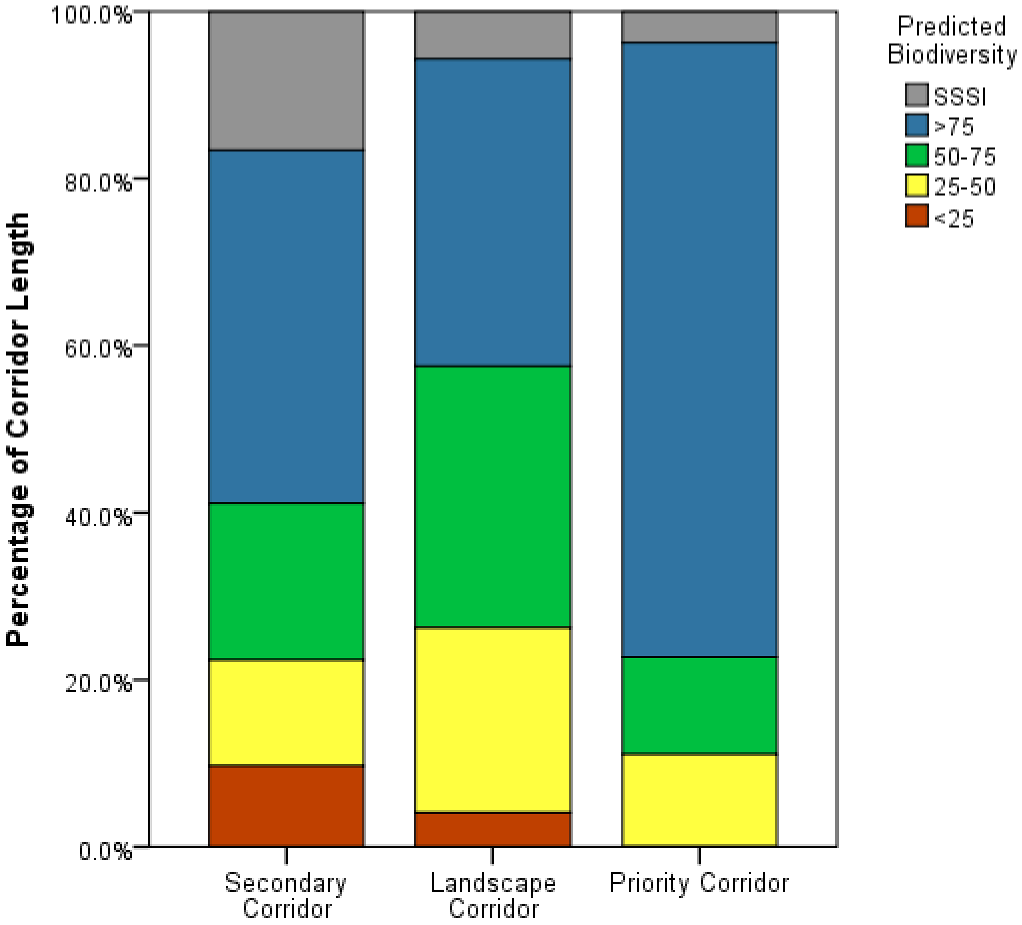


Fig. 16. Percentage of the length of each corridor type (from Fens for the Future (Keymer and Brayshaw 2012)) occurring within SSSIs and categories of predicted biodiversity value (based on the quartiles of the predicted biodiversity richness in 1 km squares, i.e. blue indicates the top quartile of biodiversity rich-squares).

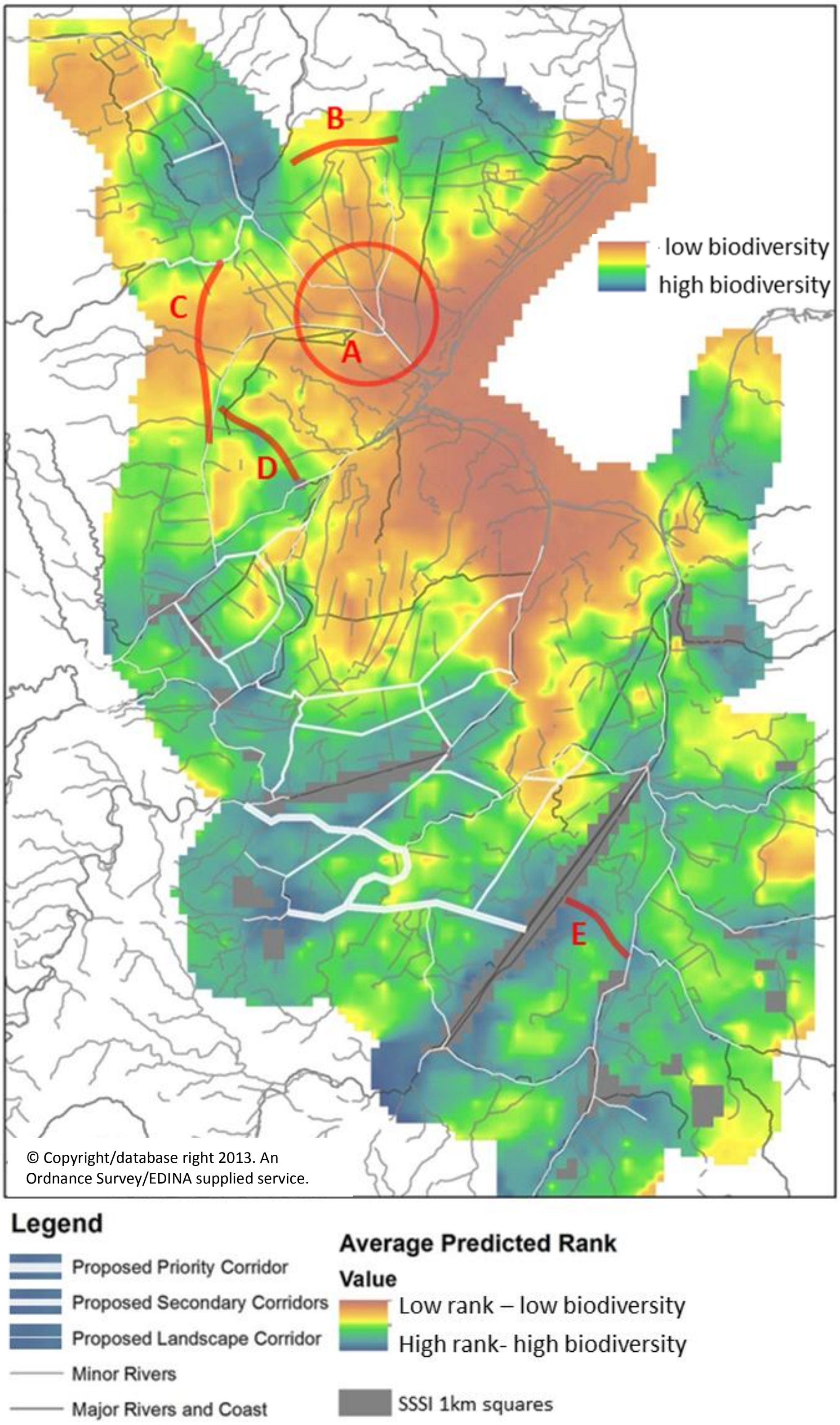


Fig. 17. The mean of the ranked predicted values for the seven biological response variables of each 1 km square, smoothed across the landscape using Inverse Distance Weighting. Brown (low rank) indicates squares with low predicted biodiversity and blue (high rank) to areas with high biodiversity. White lines denote proposed corridors. See text for explanation of the suggested modifications to the proposed corridors (red).

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Appendices

Appendix 1. Odonata species recorded in the Fens NCA area since 1987 inclusive.

Appendix 2. Guilds defined as aquatic, littoral or associated with wetland habitats.

Appendix 3. Vascular plant, stonewort and *Potamogeton* species recorded in the Fens since 1987 inclusive that were identified as 'wetland' and 'aquatic' species.

Appendix 4. Extent of soil types occurring in the Fens NCA. Classification according to NATMAP, National Soil Resources Institute, Cranfield University.

Appendix 1. Odonata species recorded in the Fens NCA area since 1987 inclusive.

Scientific Name	Common Name	RDB	BAP	Error	No. of squares	No. of records
Anisoptera (Dragonflies):						
Aeshnidae						
Aeshna cyanea	Southern Hawker				224	511
Aeshna grandis	Brown Hawker				363	970
Aeshna isosceles†	Norfolk Hawker	*	*		1	1
Aeshna juncea	Common Hawker			?	5	8
Aeshna mixta	Migrant Hawker				298	793
Anax imperator	Emperor Dragonfly				231	599
Anax parthenope	Lesser Emperor			?	8	17
Brachytron pratense	Hairy Dragonfly				166	672
Libellulidae						
Libellula depressa	Broad-bodied Chaser				70	129
Libellula fulva	Scarce Chaser	*			89	279
Libellula quadrimaculata	Four-spotted Chaser				297	972
Orthetrum cancellatum	Black-tailed Skimmer				314	862
Sympetrum danae	Black Darter			?	2	4
Sympetrum flaveolum	Yellow-winged Darter				6	11
Sympetrum fonscolombii	Red-veined Darter				4	6
Sympetrum sanguineum	Ruddy Darter				368	918
Sympetrum striolatum	Common Darter				472	1302
Zygoptera (Damselflies):						
Calopterygidae						
Calopteryx splendens	Banded Demoiselle				199	500
Coenagrionidae						
Ceriagrion tenellum	Small Red Damselfly			?	1	2
Coenagrion puella	Azure Damselfly				354	957
Coenagrion pulchellum	Variable Damselfly	*			94	384
Enallagma cyathigerum	Common Blue Damselfly				571	1573
Erythromma najas	Red-eyed Damselfly				313	898
Erythromma viridulum	Small Red-eyed Damselfly				30	84
Ischnura elegans	Blue-tailed Damselfly				745	2264
Ischnura pumilio	Scarce Blue-tailed Damselfly	*		?	1	1
Pyrrhosoma nymphula	Large Red Damselfly				118	366
Platycnemididae						
Platycnemis pennipes	White-legged Damselfly				2	2
Lestidae						
Lestes sponsa	Emerald Damselfly				323	725

† Aeshna isosceles no longer breeds in the Fens.

Appendix 2. Guilds defined as aquatic, littoral or associated with wetland habitats.

	Guild Code	Guild Description	No. priority species	No. Fens specialist species
		Aquatic guilds:		
1	O.1	open fast flowing water	3	
2	O.13	open – aquatic	10	2
3	O.13brsub	open – aquatic – bare substrate	5	1
4	O.13mdveg	open – aquatic – moderate vegetated	18	1
5	O.13wlveg	open – aquatic – well vegetated	13	1
6	O.4	open – submerged margins	11	
7	O.4brsub	open – submerged margins – bare substrate	4	2
8	O.4shveg	open – submerged margins – short vegetation	8	1
9	O.4wlveg	open – submerged margins – well vegetated	34	4
10	O.4heveg	open – submerged margins – heavily vegetated	14	3
11	POW.4	open wood – aquatic	4	
		Littoral Guilds:		
12	O.14	open – littoral	4	
13	O.14bgrnd, shveg	open – littoral – bare ground, short vegetation	6	
14	O.14mdveg	open – littoral – moderate vegetation	5	
15	O.14wlveg	open – littoral – well vegetated	20	
16	O.14swrdm	open - littoral – sward mosaics	15	
17	O.14detri	open – littoral – detritus	10	1
18	PSS.14swrdm	scattered scrub – littoral – sward mosaics	8	
19	O.6	open – terrestrial littoral	20	
20	O.6bgrnd	open – terrestrial littoral – bare ground	23	1
21	O.6wlveg	open – terrestrial littoral – well vegetated	11	1
22	O.6juxt	open – terrestrial littoral – juxtaposition	3	
23	O.6detri	open – terrestrial littoral – detritus	12	
24	CW.6	closed-canopy wood/scrub – littoral	6	
25	V.6/14	open to closed-canopy – littoral	8	
		Wetland Guilds (those listed below and including Littoral and Aquatic Guilds)		
26	O.5	open – wet	7	
27	O.5bgrnd	open – wet – bare ground	8	
28	O.5bgrnd, dist	open – wet – bare ground, disturbance	2	1
29	O.5mdveg	open – wet – moderate vegetation	34	6
30	O.5wlveg	open – wet – well vegetated	61	13
31	O.5swrdm	open – wet – sward mosaics	8	
32	O.5fungi	open – wet – fungi	1	
33	O.5carri/dung	open – wet – carrion/excrement	2	
34	PSS.5swrdm	scattered/open scrub – wet – swrdm	7	1
35	PSS.5wlveg	scattered/open scrub – wet – well vegetated	8	1
36	T/SC.5	carr – wet	19	2
37	T/SC.5swrdm	carr – wet – swrdm	6	
38	T/SC.5dead/detri	carr – wet – deadwood/detritus	11	1
39	V.5	open to closed-canopy – wet	15	
40	V.5detri/fungi	open to closed-canopy – wet – detritus/fungi	10	

Appendix 3. Vascular plant species recorded in the Fens since 1987 that were defined as wetland plant species. A subset of these was defined as aquatic plant species.

Species name	**Aquatic**	***Species name***	**Aquatic**
Flowering plants			
Achillea ptarmica		*Lycopodiella inundata*	
Acorus calamus		*Lycopus europaeus*	
Agrostis canina		*Lysimachia nummularia*	
Alisma gramineum	1	*Lysimachia vulgaris*	1
Alisma lanceolatum	1	*Lythrum portula*	1
Alisma plantago-aquatica	1	*Lythrum salicaria*	
Alnus glutinosa		*Mentha aquatica*	1
Alopecurus aequalis	1	*Mentha arvensis*	
Alopecurus geniculatus	1	*Menyanthes trifoliata*	1
Althaea officinalis	1	*Molinia caerulea*	
Anagallis tenella		*Myosotis laxa*	
Angelica sylvestris		*Myosotis scorpioides*	1
Apium graveolens	1	*Myosotis secunda*	1
Apium inundatum	1	*Myosoton aquaticum*	
Apium nodiflorum	1	*Myrica gale*	
Azolla filiculoides	1	*Myriophyllum aquaticum*	
Baldellia ranunculoides	1	*Myriophyllum spicatum*	1
Berula erecta	1	*Myriophyllum verticillatum*	1
Bidens cernua	1	*Narthecium ossifragum*	
Bidens tripartita	1	*Nuphar lutea*	1
Bupleurum tenuissimum		*Nymphaea alba*	1
Butomus umbellatus	1	*Nymphoides peltata*	1
Calamagrostis canescens		*Oenanthe aquatica*	1
Calamagrostis epigejos		*Oenanthe fistulosa*	1
Callitriche hamulata	1	*Oenanthe fluviatilis*	1
Callitriche obtusangula	1	*Oenanthe lachenalii*	
Callitriche platycarpa	1	*Oenanthe silaifolia*	
Callitriche stagnalis	1	*Ophioglossum vulgatum*	
Caltha palustris	1	*Osmunda regalis*	
Calystegia sepium		*Persicaria amphibia*	1
Cardamine amara		*Persicaria bistorta*	
Cardamine pratensis		*Persicaria hydropiper*	
Carex acuta	1	*Persicaria mitis*	
Carex acutiformis	1	*Petasites hybridus*	
Carex appropinquata		*Peucedanum palustre*	
Carex curta		*Phalaris arundinacea*	1
Carex dioica		*Phragmites australis*	1
Carex disticha		*Poa palustris*	
Carex divisa		*Polygala serpyllifolia*	
Carex elata	1	*Potamogeton alpinus*	1
Carex hirta		*Potamogeton berchtoldii*	1
Carex hostiana		*Potamogeton coloratus*	1
Carex lasiocarpa	1	*Potamogeton compressus*	1
Carex nigra		*Potamogeton crispus*	1
Carex otrubae		*Potamogeton friesii*	1
Carex panicea		*Potamogeton gramineus*	1
Carex paniculata	1	*Potamogeton lucens*	1
Carex pendula		*Potamogeton natans*	1
Carex pseudocyperus	1	*Potamogeton obtusifolius*	1
Carex pulicaris		*Potamogeton pectinatus*	1
Carex remota		*Potamogeton perfoliatus*	1
Carex riparia	1	*Potamogeton polygonifolius*	1
Carex rostrata	1	*Potamogeton praelongus*	1

Carex vesicaria	1	*Potamogeton pusillus*	1
Carex viridula		*Potamogeton trichoides*	1
Catabrosa aquatica	1	*Potentilla anserina*	
Ceratophyllum demersum	1	*Potentilla erecta*	
Ceratophyllum submersum	1	*Potentilla palustris*	1
Chenopodium rubrum		*Puccinellia rupestris*	
Chrysosplenium alternifolium		*Pulicaria dysenterica*	
Cirsium dissectum		*Ranunculus aquatilis*	1
Cirsium palustre		*Ranunculus baudotii*	1
Cladium mariscus	1	*Ranunculus circinatus*	1
Crassula helmsii	1	*Ranunculus flammula*	1
Cuscuta europaea		*Ranunculus fluitans*	1
Dactylorhiza fuchsii		*Ranunculus lingua*	1
Dactylorhiza incarnata		*Ranunculus omiophyllus*	1
Dactylorhiza maculata		*Ranunculus peltatus*	1
Dactylorhiza praetermissa		*Ranunculus penicillatus*	1
Dipsacus fullonum		*Ranunculus reptans*	
Drosera intermedia		*Ranunculus sardous*	
Drosera rotundifolia		*Ranunculus sceleratus*	1
Eleocharis acicularis	1	*Ranunculus trichophyllus*	1
Eleocharis multicaulis		*Rhynchospora alba*	
Eleocharis palustris	1	*Ribes nigrum*	
Eleocharis quinqueflora		*Rorippa amphibia*	1
Eleocharis uniglumis		*Rorippa microphylla*	1
Eleogiton fluitans	1	*Rorippa nasturtium-aquaticum*	1
Elodea canadensis	1	*Rorippa palustris*	
Elodea nuttallii	1	*Rorippa sylvestris*	
Epilobium hirsutum		*Rumex conglomeratus*	
Epilobium obscurum		*Rumex hydrolapathum*	1
Epilobium palustre		*Rumex maritimus*	1
Epilobium parviflorum		*Rumex palustris*	1
Epilobium roseum		*Sagina nodosa*	
Epipactis palustris		*Sagittaria sagittifolia*	1
Equisetum fluviatile	1	*Salix alba*	
Equisetum palustre	1	*Salix cinerea*	
Equisetum telmateia		*Salix fragilis*	
Erica tetralix		*Salix myrsinifolia*	
Eriophorum angustifolium		*Salix purpurea*	
Eriophorum vaginatum		*Salix triandra*	
Eupatorium cannabinum		*Salix viminalis*	
Fallopia japonica		*Samolus valerandi*	1
Filipendula ulmaria		*Sanguisorba officinalis*	
Fritillaria meleagris		*Schoenoplectus lacustris*	1
Galium palustre	1	*Schoenoplectus tabernaemontani*	1
Galium uliginosum	1	*Schoenus nigricans*	
Glyceria declinata	1	*Scrophularia auriculata*	
Glyceria fluitans	1	*Scutellaria galericulata*	
Glyceria maxima	1	*Scutellaria minor*	
Glyceria notata	1	*Senecio aquaticus*	
Groenlandia densa	1	*Senecio fluviatilis*	
Hippuris vulgaris	1	*Senecio paludosus*	1
Hottonia palustris	1	*Sium latifolium*	1
Hydrilla verticillata		*Solanum dulcamara*	
Hydrocharis morsus-ranae	1	*Sonchus palustris*	1
Hydrocotyle ranunculoides		*Sparganium emersum*	1
Hydrocotyle vulgaris	1	*Sparganium erectum*	1
Hypericum tetrapterum		*Sparganium natans*	1
Impatiens capensis		*Spirodela polyrhiza*	1

Impatiens glandulifera		*Stachys palustris*	
Iris pseudacorus	1	*Stellaria palustris*	1
Isolepis setacea		*Stratiotes aloides*	1
Juncus acutiflorus		*Succisa pratensis*	
Juncus articulatus	1	*Symphytum officinale*	
Juncus bufonius		*Teucrium scordium*	
Juncus bulbosus	1	*Thalictrum flavum*	
Juncus compressus		*Thelypteris palustris*	
Juncus conglomeratus		*Trichophorum cespitosum*	
Juncus effusus		*Trifolium fragiferum*	
Juncus inflexus		*Triglochin palustre*	
Juncus squarrosus		*Typha angustifolia*	1
Juncus subnodulosus	1	*Typha latifolia*	1
Juncus tenuis		*Utricularia australis*	1
Lagarosiphon major		*Utricularia vulgaris*	1
Lathyrus palustris		*Vaccinium oxycoccos*	
Lemna gibba	1	*Valeriana dioica*	
Lemna minor	1	*Valeriana officinalis*	
Lemna minuta	1	*Veronica anagallis-aquatica*	1
Lemna trisulca	1	*Veronica beccabunga*	1
Leucojum aestivum		*Veronica catenata*	1
Liparis loeselii		*Veronica scutellata*	
Lotus pedunculatus	1	*Viola persicifolia*	
Luzula pallidula		*Zannichellia palustris*	1
Lychnis flos-cuculi			
Non-flowering plants			
Chara spp.	1	*Tolypella spp.*	1
Nitella spp.	1	*Potamogeton spp.*	1

Appendix 4. Extent of soil types occurring in the Fens NCA. Classification according to NATMAP, National Soil Resources Institute, Cranfield University.

Soil classifications	Area (km^2)
Deep clay	103.61
Deep loam/over gravel/ to clay	67.35
Deep sandy	56.59
Deep silty over peat	39.36
Dune sand	1.78
Lake or water body	5.06
Loam over chalk	39.97
Loam over gravel	55.28
Loam over limestone/sandstones	20.86
Marine	57.45
Peat	264.88
Restored following coprolite working	8.37
River	2.15
Saltmarsh	36.10
Seasonally wet deep clay	1612.55
Seasonally wet deep clay over peat	152.08
Seasonally wet deep loam/red loam/to clay/silty to clayey over shale	136.00
Seasonally wet deep peat to loam	257.33
Seasonally wet deep sand	108.00
Seasonally wet deep silty	1046.82
Shallow clay over limestone	0.08
Shallow loam over chalk	54.40
Shallow loam over limestone	6.36
Shallow silty over chalk	12.55