

The potential impacts of climate change on the biodiversity of Norfolk

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Introduction

Climate change is posing, and will continue to pose, increasing risks to biodiversity (O'Neill *et al.* 2017). Changes in phenology and range were first noted more than a decade ago (Root *et al.* 2003) with many publications since. Land use change is increasingly a problem as species are being further challenged by barriers to their potential dispersal with their preferred climate across fragmented landscapes (Settele *et al.* 2014). Many studies have examined the potential future impacts of climate change on biodiversity using a variety of modelling techniques. This includes results from Wallace Initiative Phase 1 models showing the potential for range losses of greater than 50% across large fractions of species globally at warming levels of approximately 3.6 °C above pre-industrial levels (Warren *et al.* 2013).

Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) calls for "...stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system...within a time frame sufficient to allow ecosystems to adapt naturally to climate change..." (UNFCCC 1992). More recently, the Paris Climate Agreement set a goal of limiting the global average temperature increase to "well below 2°C above pre-industrial levels", and 'pursuing efforts' to limit it to 1.5°C, a challenging proposition. However, to date, countries' individual pledges in terms of emission reductions fall far short of the levels necessary to reach 2°C, much less 1.5°C. If countries actually meet their pledges it is estimated that the global temperature is

on a trajectory for ~3.2°C increase (UNEP 2016). While this is an improvement over the previous 'business as usual' estimate of 4°- 4.5°C, it is still likely to have a large impact on biodiversity.

This paper reviews the projected climate change impacts (relative to 1961-1990 baseline) on some of the biodiversity in Norfolk (including birds, mammals, reptiles, amphibians, butterflies, common macro moths, dragonflies, bumblebees, grasshoppers, shieldbugs, ferns, orchids, and some trees and shrubs). The paper concentrates on the species currently found in Norfolk (largely based on lists on the Norfolk and Norwich Naturalist's Society website) and not on potential colonists from Europe. The exception is for some of the birds and dragonflies. For brevity it concentrates on the climate changes associated with just two potential levels of warming: 2°C (the upper end of the Paris Climate Agreement) and 3.2°C (the upper limit of the NDC pledges to date).

Methods

The projected changes in biodiversity come from the Wallace Initiative Phase II and III which modelled the potential impacts of climate change on nearly 125,000 species of terrestrial plants, birds, mammals, reptiles, amphibians, and invertebrates. The methods used in this study largely follow those in Warren *et al.* 2013 and are summarized here, along with the modifications made since 2013. For a more complete review of the methods, limitations and caveats please see the Supplemental Information in Warren *et al.* (2013).

Biodiversity occurrence data were obtained from the Global Biodiversity Information

Facility (GBIF; Yesson *et al.* 2007). GBIF facilitates acquisition of data from many global datasets, including the National Biodiversity Network. Thus, some of the underlying occurrence data used in this paper may have originally come from the readers of this journal. These data were then checked and cleaned for locational consistency and outliers (Warren *et al.* 2013).

Climate data comes from the Tyndall Climate Change Centre's Community Integrated Assessment System (CIAS) and its component module ClimGEN. In this approach, a simple climate model is used to project global temperature rise probabilistically (in order to encompass the key uncertainties in state-of-the-art global climate change projection) over the 21st century. Outputs from 21 general circulation models (GCM) from a model inter-comparison project (CMIP5, used in IPCC AR5; IPCC 2013) provided the pattern of how climate variables are projected to change regionally for particular levels of global temperature rise. ClimGEN scales these patterns to the amount of warming that is provided by the time series in order to create 21 patterns of projected changes corresponding to differing levels of temperature rise (with accompanying changes in precipitation). The global temperature time series used in this study were provided by the UK Met Office Hadley Centre and used in the AVOID2 (Avoiding Dangerous Climate Change) project (Bernie & Lowe 2014). The advantage of using these scenarios is that they are internally consistent as to when a given global temperature is reached across climate models, making them more useful for comparing different policy options.

To model the potential impacts on individual species, GBIF occurrence data were combined with the climate data to develop individual species distribution models using the MaxENT (Phillips *et al.* 2006) program at a spatial scale of 10 arc

minutes (approximately 20 km x 20 km). The eight bioclimatic variables used in the models were the average maximum temperature of warmest month of the year, average minimum temperature of coldest month of the year, annual mean temperature, temperature seasonality, total annual rainfall, rainfall seasonality, rainfall of the wettest quarter, and rainfall of the driest quarter. These variables were selected after extensive testing showed them to be the best predictive variables for the broadest range of species out of the potential 18 bioclimatic variables. A reduced set of variables was used in order to minimize potential issues with autocorrelation and to prevent 'overfitting' of the MaxEnt model species distributions. Ten cross-validated runs were then performed to assess the MaxEnt model accuracy. The Area under the Receiver Operating Characteristic (AUC) was used to select species models for projection over all climate scenarios. Each future climatic range for each species was then projected into the future for each of the 21 climate models at global warming levels of 1.5°C to 6°C.

Lists of species in Norfolk were sourced from the website of the Norfolk and Norwich Naturalists' Society <http://norfolknaturalists.org.uk/wp/>, specifically the species guides. The list of birds came from <http://www.norfolkbirds.com/>; and that of common macro moths from <https://www.norfolkmoths.co.uk/macrolist>. There are many other groups, such as flowering plants, beetles, micro moths, etc. that could be looked at in future papers. Furthermore, in many taxa, especially moths, vagrants and potential immigrants have yet to be examined and some of these may increase with warming. This will be explored in a future paper. The 50th percentile (averaged across all climate models for a given temperature) map of each species on the list was then examined to see the degree of potential change (including increasing likelihood of

occurrence) at 2° and 3.2°C. Species not listed likely show no change as almost all Norfolk species had adequate models to assess potential change. It is important to understand that a model result is not a crystal ball. Potential epigenetic or behavioural changes, or persisting microclimatic habitats could allow species to persist for periods of time beyond reaching different temperatures. Similarly, for species that are common in Europe but rare in Norfolk, the English Channel forms a very real barrier to colonization owing to dispersal, with many periods of colonization and extirpation likely before a species is firmly established.

Results

Birds

Increasing likelihood of occurrence/range expansions:

Little Bittern *Ixobrychus minutus*
 Black-crowned Night Heron *Nycticorax nycticorax*
 Cattle Egret *Bubulcus ibis*
 Squacco Heron *Ardeola ralloides*
 Purple Heron *Ardea pupurea*
 Little Egret *Egretta garzetta*
 Great Egret *Ardea alba*
 European Spoonbill *Platalea leucorodia*
 European Honey Buzzard *Pernis apivorus*
 Kite *Milvus migrans*
 Montagu's Harrier *Circus pygargus*
 Hobby *Falco subbuteo*
 Little Crake *Porzana parva*
 Black-winged Stilt *Himantopus himantopus*
 Eurasian Stone-Curlew *Burhinus oedicnemus*
 Gull-billed Tern *Gelochelidon nilotica*
 Eurasian Eagle-Owl *Bubo bubo*
 Eurasian Scops-Owl *Otus scops*
 Alpine Swift *Apus melba*
 European Bee-eater *Merops apiaster*
 European Roller *Coracias garrulus*
 Eurasian Hoopoe *Upupa epops*
 Eurasian Wryneck *Jynx torquilla*
 Red-rumped Swallow *Hirundo daurica*
 Eurasian Golden-Oriole *Oriolus oriolus*
 Red-backed Shrike *Lanius collurio*
 Woodchat Shrike *Lanius senator*

Climate largely or completely unsuitable by 2°C:

Great Northern Diver *Gavia immer*
 Slavonian Grebe *Podiceps auritus*
 Bewick's swan *Cygnus columbianus*
 Whooper Swan *Cygnus cygnus*

Taiga Bean Goose *Anser fabalis*
 Pink-footed Goose *Anser brachyrhynchus*
 Red-breasted Goose *Branta ruficollis*
 Velvet Scoter *Melanitta fusca*
 Rough-legged Buzzard *Buteo lagopus*
 Grey Partridge *Perdix perdix*
 Long-tailed Skua *Stercorarius longicaudus*
 Rock Pipit *Anthus petrosus*
 Waxwing *Bombycilla garrulus*
 Lapland Bunting *Calcarius lapponicus*
 Snow Bunting *Plectrophenax nivalis*

Climate largely or completely unsuitable by 3.2°C:

Mandarin Duck *Aix galericulata*
 Smew *Mergellus albellus*
 Corncrake *Crex crex*
 Dotterel *Charadrius morinellus*
 European Golden-Plover *Pluvialis apricaria*
 Arctic Tern *Sterna paradisaea*
 Razorbill *Alca torda*
 Dunnock *Prunella modularis*
 Reed Bunting *Emberiza schoeniclus*

Mammals

Climate largely or completely unsuitable by 2°C:

Common Shrew *Sorex araneus*
 Eurasian Water Vole *Arvicola amphibius*
 Roe Deer *Capreolus capreolus*
 Soprano Pipistrelle *Pipistrellus pygmaeus*
 Nathusius' Pipistrelle *Pipistrellus nathusii*
 Brandt's Bat *Myotis brandtii*
 European Badger *Meles meles*
 Roe Deer *Capreolus capreolus*

Climate largely or completely unsuitable by 3.2°C:

Eurasian Red Squirrel *Sciurus vulgaris*
 Grey Squirrel *Sciurus carolinensis*
 Whiskered Bat *Myotis mystacinus*
 Reeves' Muntjac *Muntiacus reevesi*

Amphibians

Climate becoming more suitable/increasing likelihood of occurrence:

Natterjack Toad *Epidalea calamita*.

Climate largely or completely unsuitable by 2°C:

Common Frog *Rana temporaria*
 Great Crested Newt *Triturus cristatus*
 Smooth Newt *Lissotriton vulgaris*

Reptiles

Climate largely or completely unsuitable by 2°C:

Adder *Vipera berus*
 Common Lizard *Zootoca vivipara*

Butterflies

Climate becoming more suitable/increasing likelihood of occurrence:

Silver-studded Blue *Plebeius argus*

Climate largely or completely unsuitable by 2°C:

Grizzled Skipper *Pyrgus malvae*
Large Skipper *Ochlodes sylvanus*
Essex Skipper *Thymelicus lineola*
Swallowtail *Papilio machaon*
Orangetip *Anthocharis cardamines*
Purple Hairstreak *Favonius quercus*
White-letter Hairstreak *Satyrrium w-album*
Red Admiral *Vanessa atalanta*
Peacock *Inachis io*
Dark Green Fritillary *Argynnis aglaja*
Ringlet *Aphantopus hyperantus*

Climate largely or completely unsuitable by 3.2°C:

Small Skipper *Thymelicus sylvestris*
Green Hairstreak *Callophrys rubi*
Small Tortoiseshell *Aglais urticae*
Comma *Polygonia c-album*

Common macro moths

Climate largely or completely unsuitable by 2°C:

Orange Swift *Hepialus sylvina*
Ghost Moth *Hepialus humuli*
Six-spot Burnet *Zygaena filipendulae*
Scalloped Hook-tip *Falcaria lacertinaria*
Pebble Hook-tip *Drepana falcataria*
Chinese Character *Cilix glaucata*
Figure of Eighty *Tethes ocellaris*
Yellow Horned *Achlya flavicornis*
December Moth *Poecilocampa populi*
Pale Eggar *Trichiura crataegi*
Oak Eggar *Lasiocampa quercus*
Fox Moth *Macrothylacia rubi*
Drinker *Euthrix potatoria*
Small Emperor Moth *Saturnia pavonia*
Lime Hawk-moth *Mimas tiliae*
Eyed Hawk-moth *Smerinthus ocellata*
Poplar Hawk-moth *Laothoe populi*
Privet Hawk-moth *Sphinx ligustri*
Elephant Hawk-moth *Deilephila elpenor*
Small Dusty Wave *Idaea seriata*
Single-dotted Wave *Idaea dimidiata*
Small Fan-footed Wave *Idaea biselata*
Shaded Broad-bar *Scotopteryx chenopodiata*
Garden Carpet *Xanthorhoe fluctuata*
Red Twin-spot Carpet *Xanthorhoe spadicearia*
Dark-barred Twin-spot Carpet *Xanthorhoe ferrugata*
Flame Carpet *Xanthorhoe designata*
Silver-ground Carpet *Xanthorhoe montanata*
Yellow Shell *Camptogramma bilineata*
Streamer *Anticlea derivata*
Beautiful Carpet *Mesoleuca albicillata*
Dark Spinach *Pelurga comitata*

Mallow *Larentia clavaria*
July Highflyer *Hydriomena furcata*
May Highflyer *Hydriomena impluviata*
Pine Carpet *Thera firmata*
Spruce Carpet *Thera britannica*
Grey Pine Carpet *Thera obeliscata*
Blue-bordered Carpet *Plemyria rubiginata*
Barred Yellow *Cidaria fulvata*
Broken-barred Carpet *Electrophaes corylata*
Purple Bar *Cosmorhoe ocellata*
Phoenix *Eulithis prunata*
Chevron *Eulithis testata*
Spinach *Eulithis mellinata*
Barred Straw *Eulithis pyraliata*
Red-green Carpet *Chloroclysta siterata*
Common Marbled Carpet *Dysstroma truncata*
Dark Marbled Carpet *Dysstroma citrata*
Green Carpet *Colostygia pectinataria*
Mottled Grey *Colostygia multistrigaria*
Water Carpet *Lampropteryx suffumata*
Northern Winter Moth *Operophtera fagata*
Winter Moth *Operophtera brumata*
November Moth *Epirrita dilutata*
Pale November Moth *Epirrita christyi*
Autumnal Moth *Epirrita autumnata*
Small White Wave *Asthena albulata*
Fern *Horisme tersata*
Pretty Chalk Carpet *Melanthia procellata*
Twin-spot Carpet *Perizoma didymata*
Rivulet *Perizoma affinitata*
Small Rivulet *Perizoma alchemillata*
Sandy Carpet *Perizoma flavofasciata*
Double-striped Pug *Gymnoscelis rufifasciata*
V-Pug *Chloroclystis v-ata*
Sloe Pug *Pasiphila chloerata*
Green Pug *Pasiphila rectangulata*
Toadflax Pug *Eupithecia linariata*
Narrow-winged Pug *Eupithecia nanata*
Angle-barred Pug *Eupithecia innotata*
Ochreous Pug *Eupithecia indigata*
Common Pug *Eupithecia vulgata*
Mottled Pug *Eupithecia exiguata*
Tawny Speckled Pug *Eupithecia icterata*
Bordered Pug *Eupithecia succenturiata*
Grey Pug *Eupithecia subfuscata*
Lesser Treble-bar *Aplocera eformata*
Streak *Chesias legatella*
Early Tooth-striped *Trichopteryx carpinata*
Magpie *Abraxas grossulariata*
Clouded Border *Lomaspilis marginata*
Tawny-barred Angle *Macaria liturata*
Latticed Heath *Chiasmia clathrata*
Brown Silver-line *Petrophora chlorosata*
Bordered Beauty *Epione repandaria*
Speckled Yellow *Pseudopanthera macularia*
Canary-shouldered Thorn *Ennomos alniaria*
Dusky Thorn *Ennomos fuscantaria*
September Thorn *Ennomos erosaria*
Early Thorn *Selenia dentaria*
Purple Thorn *Selenia tetralunaria*
Scalloped Hazel *Odontopera bidentata*

Scalped Oak *Crocallis elinguaris*
 Swallow-tailed Moth *Ourapteryx sambucaria*
 Feathered Thorn *Colotois pennaria*
 March Moth *Alsophila aescularia*
 Pale Brindled Beauty *Phigalia pilosaria*
 Brindled Beauty *Lycia hirtaria*
 Oak Beauty *Biston strataria*
 Spring Usher *Agriopsis leucophaearia*
 Scarce Umber Moth *Agriopsis aurantiaria*
 Dotted Border *Agriopsis marginaria*
 Mottled Umber *Erannis defoliaria*
 Satin Beauty *Deileptenia ribeata*
 Mottled Beauty *Alcis repandata*
 Grey Birch *Aethalura punctulata*
 Common Heath *Ematurga atomaria*
 Bordered White *Bupalus piniaria*
 Common White Wave *Cabera pusaria*
 Common Wave *Cabera exanthemata*
 White-pinion Spotted *Lomographa bimaculata*
 Clouded Silver *Lomographa tenerata*
 Early Moth *Theria primaria*
 Barred Red *Hylaea fasciaria*
 Large Emerald *Geometra papilionaria*
 Little Emerald *Jodis lactearia*
 Common Emerald *Hemithea aestivaria*
 Puss Moth *Cerura vinula*
 Sallow Kitten *Furcula furcula*
 Lunar Marbled Brown *Drymonia ruficornis*
 Iron Prominent *Notodonta dromedarius*
 Pebble Prominent *Notodonta ziczac*
 Swallow Prominent *Pheosia tremula*
 Lesser Swallow Prominent *Pheosia gnoma*
 Pale Prominent *Pterostoma palpina*
 Coxcomb Prominent *Ptilodon capucina*
 Buff-tip *Phalera bucephala*
 The Herald *Scoliopteryx libatrix*
 Straw Dot *Rivula sericealis*
 Snout *Hypena proboscidalis*
 White Ermine *Spilosoma lubricipeda*
 Muslin Moth *Diaphora mendica*
 Ruby Tiger *Phragmatobia fuliginosa*
 Scarlet Tiger *Callimorpha dominula*
 Dingy Footman *Eilema griseola*
 Common Footman *Eilema lurideola*
 Fan Foot *Zanclognatha tarsipennalis*
 Small Fan-foot *Herminia grisealis*
 Spectacle *Abrostola tripartita*
 Burnished Brass *Diachrysis chrysitis*
 Golden Plusia *Polychrysis moneta*
 Beautiful Golden Y *Autographa pulchrina*
 Gold Spot *Plusia festucae*
 Marbled White Spot *Protodeltote pygarga*
 Figure of Eight *Diloba caeruleocephala*
 Grey Dagger *Acronicta psi*
 Knotgrass *Acronicta rumicis*
 Poplar Grey *Acronicta megacephala*
 The Shark *Cucullia umbratica*
 Copper Underwing *Amphipyra pyramidea*
 Mouse Moth *Amphipyra tragopoginis*
 Green-brindled Crescent *Allophyes oxyacanthae*
 Early Grey *Xylocampa areola*
 Pale Mottled Willow *Caradrina clavipalpis*
 Brown Rustic *Rusina ferruginea*
 Angle Shades *Phlogophora meticulosa*
 Small Angle Shades *Euplexia lucipara*
 Frosted Orange *Gortyna flavago*
 Rosy Rustic *Hydraecia micacea*
 Ear Moth *Amphipoa oculea*
 Flounced Rustic *Luperina testacea*
 Large Wainscot *Rhizedra lutosa*
 Bulrush Wainscot *Nonagria typhae*
 Small Wainscot *Chortodes pygmina*
 Small Dotted Buff *Photodes minima*
 Dusky Brocade *Apamea remissa*
 Clouded-bordered Brindle *Apamea crenata*
 Small Clouded Brindle *Apamea unanimitis*
 Dark Arches *Apamea monoglypha*
 Light Arches *Apamea lithoxyloa*
 Double Lobed *Apamea ophiogramma*
 Common Rustic *Mesapamea secalis*
 Rosy Minor *Mesoligia literosa*
 Beaded Chestnut *Agrochola lynchnidis*
 Brown-spot Pinion *Agrochola litura*
 Flounced Chestnut *Agrochola helvola*
 Red-lined Quaker *Agrochola lota*
 Yellow-line Quaker *Agrochola macilentia*
 The Brick *Agrochola circellaris*
 Lunar Underwing *Omphaloscelis lunosa*
 Chestnut *Conistra vaccinii*
 The Satellite *Eupsilia transversa*
 Centre-barred Sallow *Aethmia centrago*
 Grey Chi *Antitype chi*
 Dark Brocade *Blepharita adusta*
 Pine Beauty *Panolis flammea*
 Clouded Drab *Orthosia incerta*
 Small Quaker *Orthosia cruda*
 Powdered Quaker *Orthosia gracilis*
 Hebrew Character *Orthosia gothica*
 Twin-spotted Quaker *Orthosia munda*
 Hedge Rustic *Tholera cespitis*
 Feathered Gothic *Tholera decimialis*
 Antler Moth *Cerapteryx graminis*
 Nutmeg *Discestra trifolii*
 Grey Arches *Polia nebulosa*
 Bright-line brown-eye *Lacanobia oleracea*
 The Shears *Hada plebeja*
 Broad-barred White *Hecatera bicolorata*
 Varied Coronet *Hadena compta*
 Tawny Shears *Hadena perplexa*
 Brown-line Bright-eye *Mythimna conigera*
 Common Wainscot *Mythimna pallens*
 Smoky Wainscot *Mythimna impura*
 White-line Dart *Euxoa tritici*
 Garden Dart *Euxoa nigricans*
 Heart and Dart *Agrotis exclamationis*
 The Flame *Axylia putris*
 Flame Shoulder *Ochropleura plecta*
 Purple Clay *Diarsia brunnea*
 Ingrailed Clay *Diarsia mendica*
 Small Square-spot *Diarsia rubi*
 Lesser Broad-bordered Yellow Underwing
Noctua janthe

Red Chestnut *Cerastis rubricosa*
Double Dart *Graphiphora augur*
Dotted Clay *Xestia baja*
Square-spot Rustic *Xestia xanthographa*
Six-striped Rustic *Xestia sexstrigata*
Double square-spot *Xestia triangulum*
Short-cloaked moth *Nola cucullatella*

Climate largely or completely unsuitable by

3.2°C:

Common Swift *Hepialus lupulina*
Lunar Hornet Moth *Sesia bembeciformis*
Peach Blossom *Thyatira batis*
Buff Arches *Habrosyne pyritoides*
Lappet *Gastropacha quercifolia*
Blood-vein *Timandra comae*
Common Carpet *Epirrhoe alternata*
Small Phoenix *Ecliptopera silaceata*
Brindled Pug *Eupithecia abbreviata*
Larch Pug *Eupithecia lariciata*
Lime-speck Pug *Eupithecia centaureata*
Treble-bar *Aplocera plagiata*
Brimstone Moth *Opisthographis luteolata*
Peppered Moth *Biston betularia*
Waved Umber *Menophra abruptaria*
Pale Oak Beauty *Hypomecis punctinalis*
Engrailed *Ectopis crepuscularia*
Lobster Moth *Stauropus fagi*
Yellow-tail *Euproctis similis*
Pale Tussock *Calliteara pudibunda*
The Vapourer *Orgyia antiqua*
Cinnabar *Tyria jacobaeae*
Red Underwing *Catocala nupta*
Burnet Companion *Euclidia glyphica*
Dark Spectacle *Abrostola triplasia*
Plain Golden Y *Autographa jota*
Nut-tree Tussock *Colocasia coryli*
Svensson's Copper Underwing *Amphipyra berbera*
The Sprawler *Asteroscopus sphinx*
Marbled Beauty *Cryphia domestica*
Treble Lines *Charanyca trigrammica*
Dusky Sallow *Eremobia ochroleuca*
Clouded Brindle *Apamea epomidion*
Slender Brindle *Apamea scolopacina*
Cloaked Minor *Mesoligia furuncula*
Marbled Minor *Oligia strigilis*
Tawny Marbled Minor *Oligia latruncula*
Middle-barred Minor *Oligia fasciuncula*
Pink-barred Sallow *Xanthia togata*
The Sallow *Xanthia icteritia*
Blair's Shoulder-knot *Lithophane leautieri*
The Dun-bar *Cosmia trapezina*
Minor Shoulder-knot *Brachyloimia viminalis*
Common Quaker *Orthosia cerasi*
Beautiful Yellow Underwing *Anarta myrtilli*
Dot Moth *Melanchnra persicariae*
Broom Moth *Melanchnra pisi*
The Lychnis *Hadena bicruris*
The Clay *Mythimna ferrago*
Heart and Club *Agrotis clavus*
True Lover's Knot *Lycophotia porphyrea*

Autumnal Rustic *Eugnorisma glareosa*
Green Silver-lines *Pseudoips prasinana*

Dragonflies

Climate becoming more suitable/increasing likelihood of occurrence:

Southern Emerald Damselfly *Lestes barbarus*
Migrant Hawker *Aeshna affinis*
Red-veined Darter *Sympetrum fonscolombii*

Climate largely or completely unsuitable by

2°C:

Variable Damselfly *Coenagrion pulchellum*
Red-eyed Damselfly *Erythromma najas*
Brown Hawker *Aeshna grandis*
Downy Emerald *Cordulia aenea*
Broad-bodied Chaser *Libellula depressa*
Yellow-winged Darter *Sympetrum flaveolum*
Black Darter *Sympetrum danae*

Climate largely or completely unsuitable by

3.2°C:

Emerald Damselfly *Lestes sponsa*
Common Hawker *Aeshna juncea*
Four-spotted Chaser *Libellula quadrimaculata*
Ruddy Darter *Sympetrum sanguineum*

Bumblebees

Climate largely or completely unsuitable by

2°C:

Garden Bumblebee *Bombus hortorum*
Early Bumblebee *Bombus pratorum*
Heath Bumblebee *Bombus jonellus*
Red-shanked Carder Bumblebee *Bombus ruderarius*
Moss Carder Bumblebee *Bombus muscorum*
Tree Bumblebee *Bombus hypnorum*
Vestal Cuckoo Bumblebee *Bombus vestalis*
Barbut's Cuckoo Bumblebee *Bombus barbutellus*
Gypsy Cuckoo Bumblebee *Bombus bohemicus*
Four-coloured Cuckoo Bumblebee *Bombus sylvestris*
Hill Cuckoo Bumblebee *Bombus rupestris*
Field Cuckoo Bumblebee *Bombus campestris*

Climate largely or completely unsuitable by

3.2°C:

White-tailed Bumblebee *Bombus lucorum*

Grasshoppers

Climate largely or completely unsuitable by

2°C:

Mottled Grasshopper *Myrmeleotettix maculata*
Field Grasshopper *Chorthippus brunneus*
Stripe-winged Grasshopper *Stenobothrus lineatus*
Common Green Grasshopper *Omocestus viridulus*
Meadow Grasshopper *Chorthippus parallelus*
Lesser Marsh Grasshopper
Chorthippus albomarginatus
Common Groundhopper *Tetrix undulata*
Dark Bush-cricket *Pholidoptera griseoptera*
Speckled Bush-cricket *Leptophyes punctatissima*

Oak Bush-cricket *Meconema thalassinum*
Bog Bush-cricket *Metrioptera brachyptera*
Great Green Bush-cricket *Tettigonia viridissima*
Roesel's Bush-cricket *Metrioptera roeselii*
Shortwinged Conehead *Conocephalus dorsalis*

Climate largely or completely unsuitable by 3.2°C:

Slender Groundhopper *Tetrix subulata*

Shieldbugs

Climate largely or completely unsuitable by 2°C:

Birch Shieldbug *Elasmotethus interstinctus*
Juniper Shieldbug *Cyphostethus tristriatus*
Heather Shieldbug *Rhacognathus punctatus*
Red-legged Shieldbug *Pentatoma rufipes*
Forget-me-not Shieldbug *Sehirus luctuosus*
Hawthorn Shieldbug *Acanthosoma haemorrhoidale*
Parent Bug *Elasmucha grisea*
Bronze Shieldbug *Troilus luridus*
Common Green Shieldbug *Palomena prasina*
Small Grass Shieldbug *Neottiglossa pusilla*
Dock Bug *Coreus marginatus*

Climate largely or completely unsuitable by 3.2°C:

Bishop's Mitre Shieldbug *Aelia acuminata*
Blue Shieldbug *Zicrona caerulea*
Crucifer Shieldbug *Eurydema oleracea*
Gorse Shieldbug *Piezodorus lituratus*
Hairy Shieldbug *Dolycoris baccarum*
Woundwort Shieldbug *Eysarcoris venustissimus*
Tortoise Shieldbug *Eurygaster testudinaria*
Bordered Shieldbug *Legnotus limbosus*
Box Bug *Gonocerus acutaeangulatus*
Denticulate Leatherbug *Coriomeris denticulatus*
Heath Shieldbug *Legnotus picipes*
Pied Shieldbug *Tritomegas bicolor*
Spiked Shieldbug *Picromerus bidens*

Ferns

Climate largely or completely unsuitable by 2°C:

Moonwort *Botrychium lunaria*
Crested Buckler Fern *Dryopteris cristata*

Orchids

Climate largely or completely unsuitable by 2°C:

Pugsley's Marsh Orchid *Dactylorhiza traunsteineri*

Climate largely or completely unsuitable by 3.2°C:

Green-flowered Helleborine *Epipactis phyllanthes*
Creeping Lady's-tresses *Goodyera repens*
Common Spotted Orchid *Dactylorhiza fuchsii*
Early Marsh-orchid *Dactylorhiza incarnata* and
Southern Marsh-orchid *Dactylorhiza praetermissa*

Trees and shrubs

Climate largely or completely unsuitable by 2°C:

European larch *Larix decidua*

Climate largely or completely unsuitable by 3.2°C:

European Aspen *Populus tremula*
Downy Birch *Betula pubescens*
Silver Birch *Betula pendula*
Horse Chestnut *Aesculus hippocastanum*
Rowan *Sorbus aucuparia*
Bird Cherry *Prunus padus*
Eared Willow *Salix aurita*
Goat Willow *Salix caprea*
Osier *Salix viminalis*
Western Hemlock *Tsuga heterophylla*
Hybrid Larch *Larix marschliinii*
Scots Pine *Pinus sylvestris*
Norway Spruce *Picea abies*
Sitka Spruce *Picea sitchensis*

Summary

The findings presented here come from the most comprehensive global analysis to date of projected losses in the climatic ranges of plants and animals; nevertheless, all factors of potential importance to a given species could not be included in the analyses. For example, it is unclear how and to what extent species might utilise novel climates, as they need to be able to disperse to them. Changes in the severity of extremes of atmospheric weather and climate variables, such as temperature and precipitation extremes, might exceed the survivability thresholds of some species before the mean climate becomes unsuitable, as has been shown for butterflies in the UK (McDermott Long *et al.* 2017).

The impacts on the biodiversity of Norfolk rapidly increase with increasing temperatures. Under the current Paris pledges a temperature rise of 3.2°C potentially could have major impacts on biodiversity, with even 2°C potentially significantly impacting the species of Norfolk. However, warming of 1.5°C (not shown) could offset many of the potential losses of species' ranges in Norfolk.

Species distribution models should not be considered as 'crystal balls' of the future.

Monitoring, especially by members of the NNNS, will help assess which species over time seem to be tracking the climate and which are not, and the data collected can help to inform the next generation of models. Nevertheless, uncertainties in models are not reasons for complacency or uncertainty paralysis. The potential impacts to some taxa are large, and could have impacts on species otherwise less exposed to climate change.

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The effects of climate change on Norfolk Wildlife Trust reserves will be considered in a future paper.