ECOLOGICAL RESPONSES TO CLIMATE VARIABILITY IN WEST CORNWALL

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I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

Signature..

To my Mum and Dad

Abstract

Recent (post-1950s) climate change impacts on society and ecosystems have been recognised globally. However these global impacts are not uniform at regional or local scales. Despite research progress on such scales there are still gaps in the knowledge as to 'what' is happening and 'where'? The goal of this study addresses some of these gaps by analysing climate variability and vegetation response at the furthest south westerly peninsula of the United Kingdom. This research is focused on West Cornwall (South West England) – an area dominated by a strong maritime influence. The first part of this PhD research analysed archive and contemporary instrumental data in order to detect any trends in climate variability. The weather data was retrieved from the Met Office archive for Camborne 1957–2010 and Culdrose 1985–2011 stations; Trengwainton Garden (1940–2010), and from the Royal Cornwall Polytechnic Society, for Falmouth (1880–1952) and Helston (1843–1888). The data showed positive trends in mean annual and maximum temperature with the largest trend magnitude in the 20th and 21st century. Seasonal temperature change varies locally with the highest increase in autumn spring and summer. Precipitation trends were only positive for the 19th century for Helston. Correlation between precipitation data and North Atlantic Oscillation (NAO index) was negative, however the opposite result was detected when the NAO index was correlated with temperatures. Surprisingly, return period analysis showed a decrease in the frequency and intensity of extreme precipitation events post 1975 for Camborne and Trengwainton Garden stations. The second part of this study analysed changes in vegetation distribution in West Cornwall using historical and contemporary vegetation records. Historical vegetation records were used from the Flora of Cornwall collection of herbarium records and contemporary vegetation records which were available online, containing mainly the "*New Atlas of British and Irish flora"*. Data sets were geo-referenced using ArcGIS in order to analyse changes in species geographical distribution pre and post-1900. Analysis showed that historical vegetation records can be used to assess any changes in geographic distributions of vegetation. Analysis for the area of West Cornwall showed a loss of range for 18 species, for 6 species this loss was larger than 50% of the area, and there was no change in overall range area for 10 species. Ellenberg values and environmental indicator values showed that they can be used as an indicator of environmental change, showing a decrease in species with lower January temperatures. Analysis also showed an increase in moderate wetter species, where species with extreme low and high precipitation environmental indicator values showed a greater loss. Furthermore species with a higher requirement for light showed a loss as well as species with lower nitrogen values. To analyse the loss of species at the local scale, West Cornwall was divided into three areas (North Border Cells, Central West Cornwall Cells and South Border Cells). The highest loss of 11 species was detected for South Border Cells, where the loss for Central West Cornwall Cells was 6 and for North Border Cells 8 species. It was found that 17 species were experiencing loss on different local sites. For 9 of these 17 species, change at the local scale was different to the national scale change at the individual species level, group level and habitat level. Furthermore, the whole area of West Cornwall lost two species post-1900, with a different loss locally. This showed that species could be protected locally in appropriate microclimate refugia, which will be of benefit for the preservation of regional identity ecosystem services and overall genetic pool of the species.

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For all sorts of reasons, this PhD has been a very long and tiring process. It has also been a journey of constant learning and improving of myself; as a researcher and as a person. This is why at the end of this writing process there are quite a few people that I would like to say thanks as they all contributed in their unique, personal way to this PhD and without them none of this would be possible.

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1. Introduction

1.1 Research context

Changes in the climate system have been observed at the millennial and centennial scale and these historical changes have been attributed to natural drivers (e.g. solar irradiance, volcanism) (Ammann et al. 2007; IPCC WG1 5AR 2013a). However, recent climate change (i.e. 20th and 21st century) cannot be explained by natural climate variations alone (Crowley 2000; Moberg et al. 2005; Hansen et al. 2012; IPCC WG1 5AR 2013a). The main drivers of this climate change are increased levels of greenhouse gasses (GHGs) (e.g. carbon dioxide (CO_2), methane (CH_4) and sulphur dioxide (SO_2)) input to the atmosphere during the industrial era (post-1850), (Karl and Trenberth 2003; Hegerl et al. 2006; IPCC WG1 5AR 2013a). Increased levels of GHGs are the result of human activities such as fossil fuel burning and land use change (primarily deforestation and changes in agricultural practices). The role of GHGs is to keep Earth warm (without them it would be 33°C cooler) (Met Office 2014a). However, with increased levels of GHGs more long wave radiation that has been reflected from the Earth, has been absorbed and re-emitted back to the surface creating a warmer atmosphere. This increased warming creates positive feedbacks such as water vapour and albedo feedbacks, carbon and methane cycle feedbacks, all creating further warming of the atmosphere (Cox et al. 2000; Scheffer et al. 2006; Walter et al. 2006).

Therefore, an anthropogenic or post-industrial (post-1800) climate change impact is visible through an increase in global average temperatures, changes in extreme events, precipitation, change in biodiversity range and loss, and also reduction of Greenland and parts of Antarctic ice sheets mountain glaciers, and sea level rise (Cazenave 2006; Church and White 2006; Rosenzweig et al. 2008; Cardinale et al. 2012).

These impacts are visible globally but the magnitude and direction of the changes differs regionally and locally (e.g. some regions have been experiencing an increase in temperature, precipitation and extreme events, whilst other regions experience a decrease) (Trenberth 2011; IPCC WG1 5AR 2013a). Climate change impacts affect ecosystem and society (e.g. floods, droughts heat and cold waves) and in order to provide an understanding and better adaptation strategies, there is a need for regional-local climate change research; however such research depends on the availability of accurate and consistent instrumental archive records (Folland et al. 2002; Beniston 2004; Beniston et al. 2007; Gobiet et al. 2014). Furthermore, regional research on climate variability using instrumental archive data, allows not just an understanding of past changes at the fine scale (e.g. at regional and local extents), but may also provide a data-baseline that can be incorporated into Regional Climate Models (RCMs) as climate projections by Global Climate Models (GCMs) cannot give accurate estimates for the regional scale due to their large grid size and broad resolution (Haylock et al. 2008; IPCC WG1 5AR 2013b). A good availability of archive instrumental data (i.e. daily data describing temperature and precipitation) allows analysis of extreme events and also correlation with regional teleconnections (i.e. North Atlantic Oscillation-NAO index) as it is known that teleconnections affect weather patterns at the broader scales (e.g. national or continental), but what is less clear is how they affect weather patterns at a regional scale or local scale (Hurrell et al. 2003). Understanding of local climate variability (i.e. microclimates) creates a basis for future conservation strategies to enable species to migrate in the face of climate change (Turlure et al. 2010; Scherrer and Körner 2011).

The impact of climate change on biodiversity has been recognised through changes in phenology, geographic distributions, species extinction, invasive species intrusions and in different growing rates in species that require higher or lower CO_2 (i.e. C3 and C4 plants) for their photosynthesis (Davis and Shaw 2001; Parmesan 2007; Parmesan et al. 2011). Understanding changes in species geographic distribution and species extinction at the regional and local scale allows an understanding of which species are more vulnerable to climate change (Parmesan et al. 2000; Walther et al. 2002; Mieszkowska et al. 2006). As climate change is not the only anthropogenic factor that has an impact on biodiversity (e.g. land use change) there is a need to establish the attribution of biodiversity change to climate change (Parmesan 2006; Smith et al. 2006; Ordonez et al. 2014). In order to make this comparison and investigate these patterns at the regional and local scale, it is necessary to have historical data with a good spatial and temporal coverage, and as this study will concentrate on vegetation change it is important to have herbarium records (Elith and Leathwick 2007; Crawford and Hoagland 2009; Feeley 2012). Regional and local research on changes in vegetation distribution allows comparison with species change at the national scale, it also enables the analysis of the association of vegetation change to the regional/local climate variability, and therefore the ability to identify whether Ellenberg/environmental indicator values can show which species are more vulnerable to abiotic changes (Feeley and Silman 2010; Scherrer and Körner 2011). This is important as it can be another step towards a missing link in attributing vegetation response to climate change. Knowledge of species range reductions at a local scale can help in future research on genetic diversity between populations and on evolutionary mechanism (Alsos et al. 2009; Turlure et al. 2010; Alsos et al. 2012).

The Figure 1 represents the context of this research and it has been divided in two parts (a & b). The first part of Figure 1 represents a broad theoretical framework, within which this research falls. The effects of climate change, in the 20th and 21st centuries, are visible in the climate system through temperature change, precipitation change and change in extreme events (Chou et al. 2009; IPCC WG1 5AR 2013a; Herring et al. 2014). Although an increase in global temperatures has been detected such changes are still regionally variable, whereas an uniform trends for precipitation or extreme events are much harder to detect, due to their high temporal and spatial variability (Orlowsky and Seneviratne 2012; Greve et al. 2014). Hence, to understand changes in the climate system regionally and locally, there is a need for more small scale research. Anthropogenic climate change also impacts biodiversity, and such changes can be detected in a change of range and the loss of species (Skov and Svenning 2004; Lavergne et al. 2006; Parmesan et al. 2011; Bellard et al. 2012; Moritz and Agudo 2013). Another impact on biodiversity is visible through land use change, as todays pressure on ecosystems is extremely high, due to the increase in human population and, as a result, an increased need for new resources. Furthermore, invasive species could also affect the changes in geographical distribution of biodiversity (SCBD 2014; Van Kleunen et al. 2014). However, both invasive species intrusions and land use change are not part of this PhD research. Although, climate change has impact on biodiversity it is also known that biodiversity loss impacts climate change through positive climate change feed (e.g. carbon emissions). Positive climate change feedback is not in the scope of this PhD study.

The second part of Figure 1 presents the framework of this research on the small scale. This research will analyse locally available historical and contemporary instrumental data from West Cornwall, in order to detect any changes in climate variability. To analyse changes in geographical distribution of plant species in West Cornwall and detect possible local losses, over the last 200 years, all available historical vegetation records (herbarium collections) and contemporary vegetation records were used. Ellenberg values (established for plant species as a measure of sensibility towards abiotic factors) were used to understand whether they can be a proxy for environmental change, and a possible link between vegetation change and climate change.

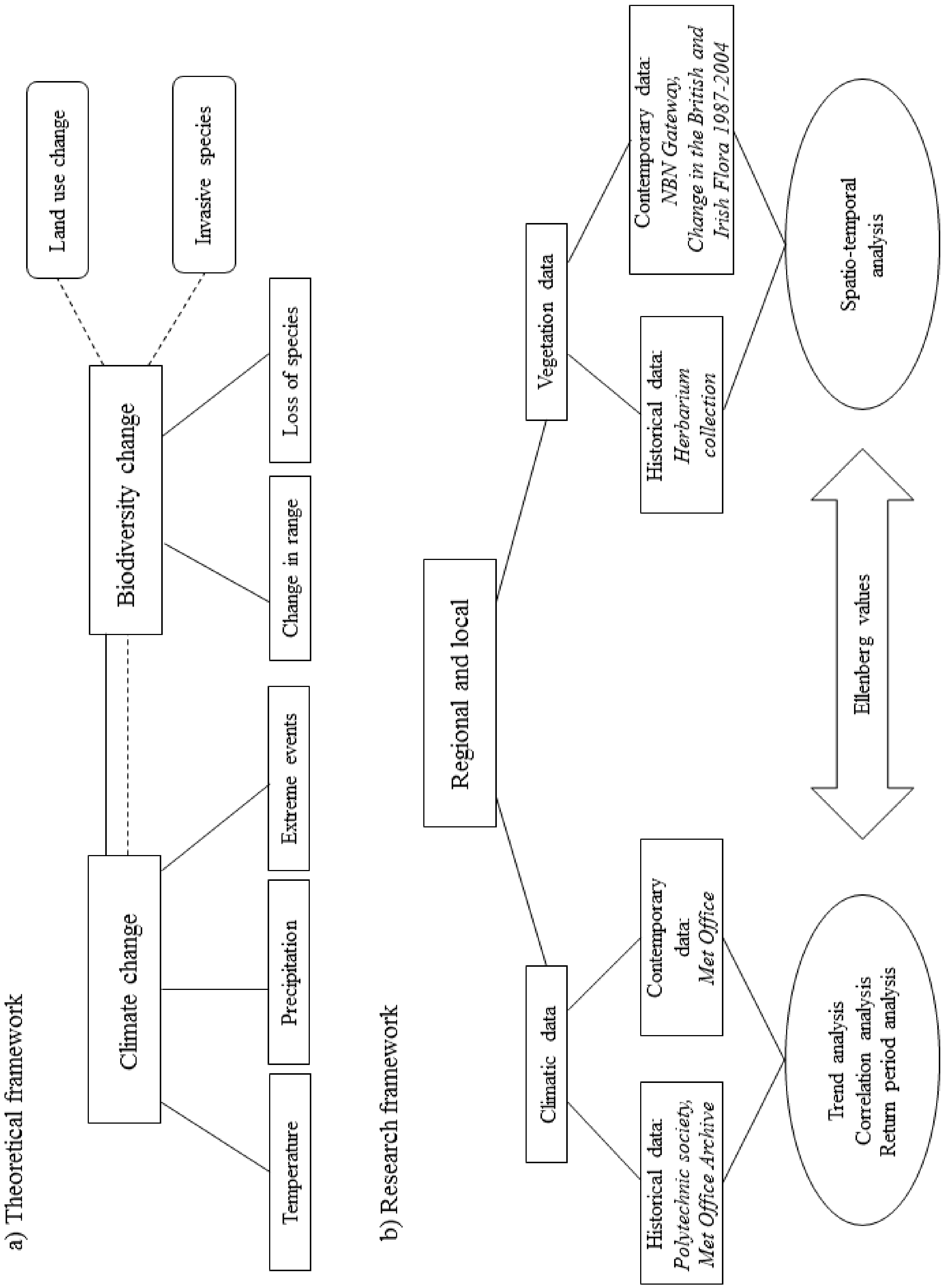


Figure 1 The framework of this research showing broader theoretical part of the topic and framework of this particular study

1.2 Research aims

This section outlines the aims and objectives for evaluating climate variability and vegetation responses. This thesis is an interdisciplinary research project, presenting research that addresses questions focusing on climate change and ecological research. The aims of this research are to develop a methodology that explores interconnections between these two fields. The first aim of this research is to provide an improved understanding of climate variability in West Cornwall during the 19th, 20th and 21st century, using temperature and precipitation datasets derived from historic and contemporary meteorological records. The second aim is to assess the impact of climatic change in this region on local vegetation communities using a new method, utilising the historic 'herbarium' vegetation record called, "The Flora of Cornwall" (Davey 1909). The third aim of this research is to find a link between local climate variability and species distributional change in order to detect species vulnerable to abiotic changes in the environment. The following list details the objectives of this research in relation to each aim:

Aim 1: understanding climatic variability

1. To analyse climate variability on the local scale over West Cornwall, using historical and contemporary weather data

   The first objective (1) was to use local historical and contemporary weather records to understand climate variability at the local scale. For this it is crucial that the study area has a good spatial and temporal availability of historical weather records (e.g. temperature, precipitation) (Millar and Woolfenden 1999; Tsutsui and Suarez 2004; Brunet and Jones 2011), which is the case with West Cornwall. The current availability of instrumental weather records in digital form is mainly restricted to the 20th century. Although this can limit research on climate variability on a longer (centennial) scale, in this case, longer (from 19th century), non-digitised instrumental weather records do exist in archives, in textual form. In order to make this project feasible, extraction of archive instrumental data was a necessary, but time consuming step.

2. Investigate whether there is a correlation between the magnitude of the NAO index and annual and seasonal average of maximum and minimum temperature and annual and seasonal average precipitation

The second objective (2) was to investigate whether temperature and precipitation data correlate with both the PC and station based NAO indices to provide improved understanding of local climate variability.

3. Investigate extreme precipitation events for stations with daily data

The third objective (3) of this research analysed return periods of precipitation events to determine whether there was any change in frequency and intensity. In this project, this was achievable for two weather stations, Camborne and Trengwainton Garden.

Aim 2: Understanding vegetation change in West Cornwall

4. Develop a methodology to digitise historical vegetation data from uncertain herbarium records

The fourth (4) objective was to analyse weather historical vegetation records (i.e. hobbyist herbarium records collected in the 18th and 19th century (Davey 1909)), could be used to track changes in geographical distribution of plant species and detect their loss in West Cornwall. Historical/herbarium data requires digitisation; this is a challenging task as manual geo-referencing brings more uncertainties, which needs to be tackled. Nevertheless historical data is important in order to track the changes in geographical distribution of plant species.

5. Investigate changes in the geographic distribution of vegetation at the local scale of West Cornwall

The fifth (5) objective will investigate local changes in the geographic distribution of plant species in order to detect potentially vulnerable plant species.

6. Investigate the loss of plant species locally and, at the range of West Cornwall, address the importance of local vegetation conservation.

The sixth (6) objective will investigate loss of plant species locally as well as any overall loss from the range of West Cornwall in order to demonstrate why local conservation is important for conservation policy.

Aim 3: understanding links between local climate variability and species distributional change

7. Investigate whether Ellenberg values can be used as a proxy for abiotic environmental change and therefore a link for climate change detection

   The seventh objective (7) is to investigate whether Ellenberg values could be used as a proxy for the environmental change and climate change detection as this is a current missing link in correlating vegetation change to the climate change at the regional or local scale (Parmesan et al. 2011).

1.3 Thesis structure

This structure of this is organised around empirical chapters that are presented in the form of research papers. This thesis begins with an introduction (Chapter 1), followed by a literature review in Chapter 2. The first part of the second chapter presents current research on global climate change impacts and vegetation response to it. It also provides an insight into why historical data (weather and vegetation) are crucial for this type of research. The second part (Chapter 2) pays particular attention to national scale climate change research, showing regional future projection estimates for South West England and uncertainties that follow such projections. This section also presents research on vegetation response at the national scale, and shows why this type of research is important from the regional to the local scale and the role of policy makers. Although methods used in this PhD research are presented as a part of each research paper Chapter 3 provides a more detailed overview and explanation of the methodology in detail and gives a complete description of the study site. Chapter 4 is the first empirical chapter presented in the form of a research paper and has been published (Kosanic et al. 2014b). This chapter addresses objectives 1, 2, and 3. Chapter 5 is the second empirical chapter in the form of a second research paper: "Plant species response to climatic variability on the West Cornwall peninsula (South West England)", which was submitted to the *Climatic Change Journal* on 31/11/2014 and this chapter present results that address objectives 4, 5 and 6. Chapter 6, is the third empirical chapter, also in the form of a paper, which is currently in the review process; "Vegetation change over West Cornwall (South West England) in response to climate change and the importance of local conservation". This chapter addresses objective 7. This paper has been submitted to the *Global Ecology and Conservation* and it is currently in a review process. The first part of (Chapter 7) will bring together all of the previous results in overall discussion whereas the second part of the same chapter will gather findings from this research project into the conclusion.

2. Literature review

2.1 Science of the climate system

Palaeoclimatic research provides has been used to provide assessments of the drivers and consequences of past climate change, and has been used to contribute to better understanding of contemporary and future changes (Bradley 2015). The current geological period in which the human race emerged and evolved is the Quaternary (which started ~2.6 Ma ago), and has been divided into two epochs the Pleistocene (~2.6 Ma to ~11.7 Ka) and Holocene, (~11.7 Ka until present) (Head et al. 2008; Walker et al. 2009; Bradley 2015).

Palaeo data analysis (especially from ice cores and marine sediments) showed that Pleistocene was characterised by a series of glacial and interglacial events, and it has been estimated that during peak glaciation average global temperatures were lower by ~5°C compared with temperatures today (Jørgensen 2010). These variations of the Earth's climate can be attributed to the natural variability; volcanic eruptions, solar activity and Milankovich cycles (i.e. changes in orbital eccentricity, changes in the Earth's axial tilt and changes in procession of the Earth's axis) which resulted in changed seasonal insolation and geographical distribution of the Sun insolation (Pyle et al. 2006; Nisancioglu 2009; Robock et al. 2009; Bradley 2015). In the Holocene, the climate was more stable than in the early Quaternary and this allowed the gradual development of civilisation and an increase in human population (deMenocal 2001; Batterbee and Binney 2008). The period between the Mid Holocene and post-industrial era (6000BP-1800AD), was particularly interesting because of the availability of regionally detailed palaeoclimatic proxies and because boundary conditions of the climate system through this period did not change dramatically (Wanner et al. 2008). During this period in the Northern Hemisphere particularly, climate variation, includes Medieval Warm Period (~950-1250AD) (elsewhere called the Medieval Warm Epoch, Medieval Climate Optimum (Schöne and Fiebig 2009) or Medieval Climate Anomaly (Xoplaki et al. 2011; Moreno et al. 2012)) and Little Ice Age (~1550-1850 AD), and these variations in climate is generally explained by combinations of natural climate drivers variability (i.e. orbital, solar or volcanic forcing or the operation of internal variability in the climate system) (Ammann et al. 2007; Wanner et al. 2008; Mann et al. 2009; Miller et al. 2012). Post-industrial climate change is attributed to a combination of both natural variability and anthropogenic impacts and increase in GHG emissions (Hegerl et al. 2006; Ammann et al. 2007; Ruddiman 2007; IPCC WG1 5AR 2013a). The goal of this PhD research is to analyse local scale climate change in the post-industrial era (post-1800 AD) in order to better understand the pressure that has been placed on the Earth's systems (e.g. climate system, ecosystem). This anthropogenic impact on climate system will be discussed in following sections.

2.2 What is Climate Change- its global importance, and recognised trends

A clear anthropogenic impact on climate change has been detected from the mid-20th century to the present, and increased levels of greenhouse gasses (GHGs) has been recognised as a key driver of this change, although natural drivers of climate change such as orbital changes, volcanic eruptions, and solar irradiance cannot be excluded as important drivers of historical climate change (Robock and Free 1995; Crowley 2000; Stott et al. 2000; Karl and Trenberth 2003; IPCC WG1 4AR 2007; Wanner et al. 2008; IPCC WG1 5AR 2013a). Research on present and 20th century climate change, shows recent decades exhibit higher global temperatures than in the historic past, when the change was attributed to natural variability alone (Mann et al. 1998; Crowley 2000). To better understand anthropogenic and natural drivers impact on climate, they are compared and measured through radiative forcing (RF); a concept that is used to quantify the sensitivity of a climatic system (IPCC WG1 4AR 2007). RF can be defined as the measure of an energy factor change between incoming and outgoing energy in the Tropopause in units of Watts per square metre (W/m^2) (Iacono et al. 2008), where positive RF indicates atmospheric warming and negative RF atmospheric cooling (IPCC WG1 5AR 2013a). In the latest IPCC report it has been reported that changes in natural forcing (solar irradiance and volcanism) do not constitute a large portion of overall net radiative forcing (IPCC WG1 5AR 2013a), and therefore do not contribute largely to the increase in global temperatures.

An increase in the global mean temperatures has been detected from the 1950s, and the last decade between 2002 to 2011 was by 0.77- 0.80°C warmer than any other decade since 1800 (EEA 2012) (Fig. 2). Future projections of global temperature change produced by Global Climate Models (GCMs) are consistent in showing the increase; however future projections depend sensitively on different GHGs emission scenarios. The latest IPCC report sets new emission scenarios, called Representative Concentration Pathways (RCPs), where each scenario is named by a different level of radiative forcing (i.e. RCP2.6; RCP4.5, RCP6, and RCP8.5). Based on CMIP5 model outputs, an increase in mean global temperature by the end of the 21st century, with the low emission scenario and therefore low radiative forcing (RCP2.6= +2.6 W/m^2) is estimated to be 1.0°C where the increase with the highest GHGs emission scenario (RCP8.5= +8.5 W/m^2) is estimated to be 3.7 °C (IPCC WG1 5AR 2013a).

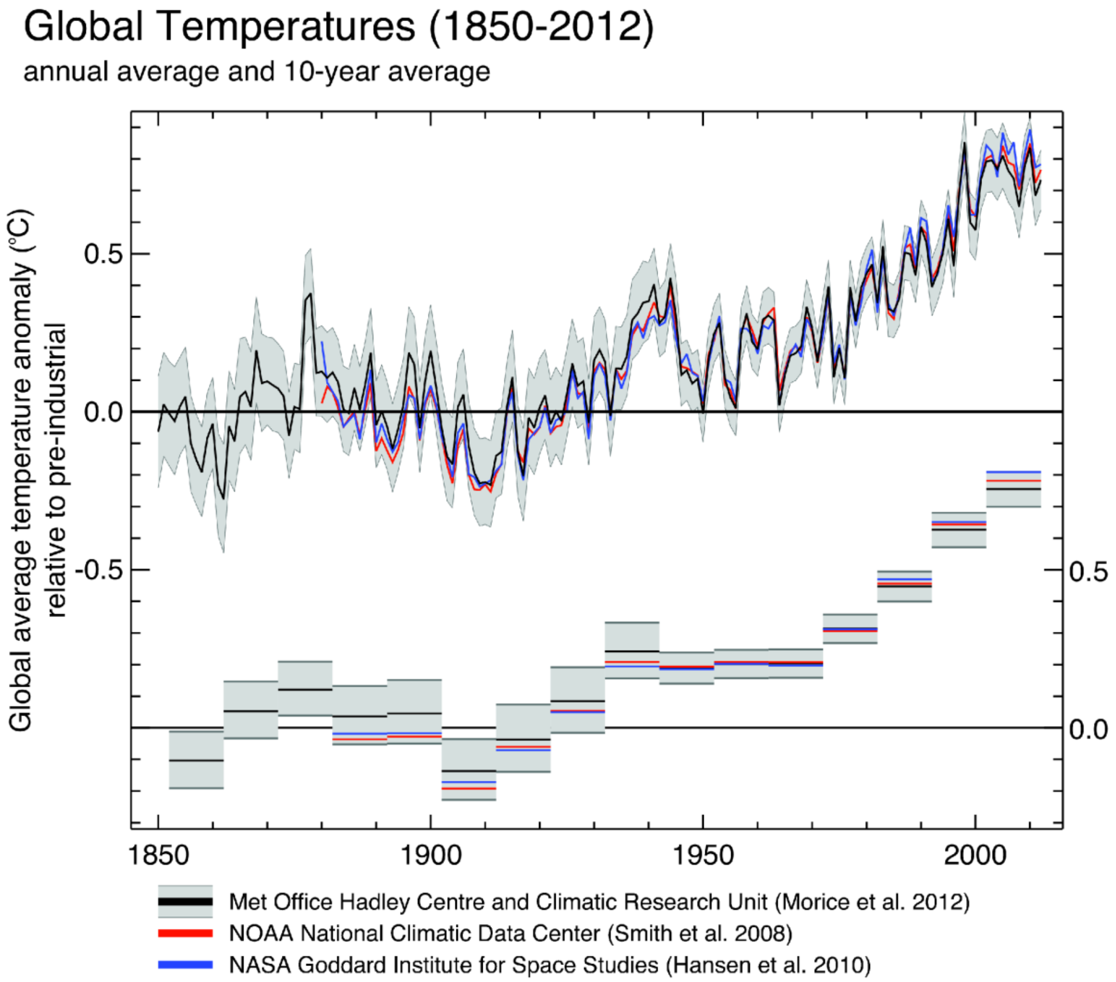


Figure 2 Global temperature change (1850-2011) in °C relative to the pre-industrial baseline period for three analyses of observations. 1) Met Office-black line, baseline period 1850-1899; 2) US National Oceanic and Atmospheric Administration (NOAA)-

red line, baseline period 1880-1899; 3), National Aeronautics and Space Administration (NASA)-blue line 1880-1899. Grey are represents 95% confidence range. The upper graph shows annual anomalies where lower graph shows decadal average for the same datasets (EEA 2012).

Beside the observed rise in temperature, there are also detected changes in precipitation and changes in the frequency and intensity of extreme events (Crowley 2000; Groisman et al. 2005; Alexander et al. 2006b; Church and White 2006).

However, trends in global precipitation are much harder to detect and to predict as precipitation is influenced by topographic variability, atmospheric circulation patterns (e.g NAO index), the current inability to parameterise cloud processes in GCMs, and therefore is more spatially and temporally variable than temperature (Solomon et al. 2010; Gobiet et al. 2014). Analysis on Earth's 20th century global mean precipitation showed an increase for most of the land areas and this pattern will probably continue, however some regions will experience a decrease in precipitation (New et al. 2001). Throughout the literature it has been proposed that drier areas will get drier and wet areas will get wetter (Held and Soden 2006; Chou et al. 2009), however Greve et al. (2014) showed that only 10.8% of global land area will follow that pattern, whereas 9.5% of global land area will follow a pattern where dry areas will get wetter and wet areas will get drier. Changes in precipitation will vary regionally and it would be too simplistic just to account for the intensification of existing trends (Greve et al. 2014).

Extreme weather events are projected to be even more intense and frequent in the future, producing a large impact on natural systems and society (Easterling et al. 2000a; Diffenbaugh et al. 2005). However, extreme events and their estimated change will vary regionally and locally. Therefore more analysis of extreme events on these scales is needed. It is important to gain more understanding of climate change drivers and feedbacks in order to develop a knowledge of what might be a 'win scenario' (a desirable level of GHGs) (Fig. 3), which will help in developing appropriate mitigation and adaptation strategies in order to minimise climate change impact. The following section offers a summary of the anthropogenic change drivers.

2.2.1 Climate change drivers

The key drivers of recent climate change are increased levels of GHGs and halocarbons caused by fossil fuel burning, deforestation and changes in land use (extensive cattle raising and increased use of synthetic fertilizers) (IPCC WG1 4AR 2007). Some GHGs are well-mixed in the atmosphere and with a long atmospheric residence, while some of them are short lived. Long lived GHGs such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (NO_2) are producing a long term impact on the atmosphere and radiative forcing, and can stay in the atmosphere for decades and even centuries, whereas short-lived GHGs, such as sulphur dioxide (SO_2), carbon monoxide (CO) and tropospheric ozone (O_3) have a shorter-term impact as their decomposition from the atmosphere is much faster (e.g. an average lifetime of few weeks) (Hofmann et al. 2006; IPCC WG1 4AR 2007; Hepburn and Stern 2008). An increase in all GHGs, particularly carbon dioxide (CO_2), the highest contributor to the observed positive RF, has been evident since the pre-industrial era. For example atmospheric CO_2, increased in the past 250 years (Fig. 3) from 250 ppm up to 401.33 ppm recorded for April 2014 the first time in human history it exceeded 400 ppm. It is expected to rise to between 700 and 800 ppm by the end of the 21st century (IPCC WG1 4AR 2007; Talmage and Gobler 2011; Portmann et al. 2012; IPCC WG1 5AR 2013a). With a continuation of current emission rates of CO_2 and NO_2 their accumulation rate in the atmosphere will increase even further, and result in an increasing contribution to positive radiative forcing (Maljanen et al. 2003; Hofmann et al. 2006). On the other hand, the halocarbons impact on positive radiative forcing has decreased. Furthermore, it has been known that the global contribution of CH_4 towards the positive radiative forcing has been constant; nevertheless, the last IPCC reports a positive RF due to the indirect effect of stratospheric ozone and water vapour (Hofmann et al. 2006; IPCC WG1 5AR 2013a). Stratospheric ozone and water vapour are crucial components in the process of CH_4 removal from the atmosphere, and therefore their possible decrease due to higher emission rates of NO_2, which decrease the stratospheric ozone and in turn can lead to a further increase of CH_4 (Portmann et al. 2012). Long lived GHGs create a positive climate feedback, producing more warming in the atmosphere, and this will be explained in a following paragraph.

Atmospheric aerosols, whether they occur naturally (i.e. volcanic aerosols) or as a result of anthropogenic activities (i.e. sulphates, smoke, dust and haze), are currently understood to contribute a negative radiative forcing. Even if the magnitude of this continues to be the largest uncertainty in RF (Haywood and Boucher 2000; Kulmala et al. 2012), it will not change the overall trend of a positive RF and a consequent increase of global temperature. How this will affect regional and local climate has to be answered and for this we need an understanding of previous climate variability, which is one of the aims of this study.

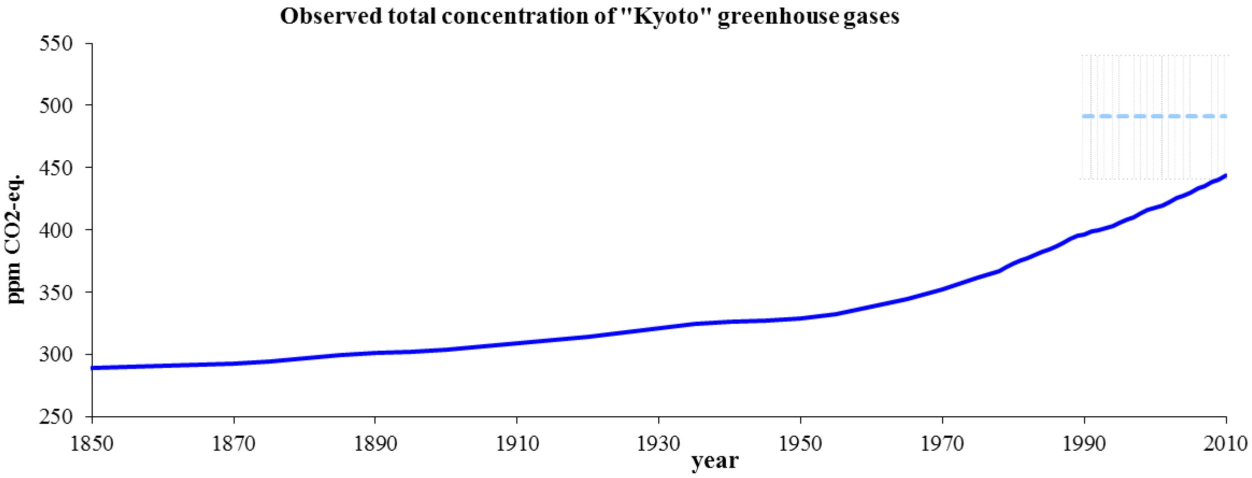


Figure 3 The figure shows the global atmospheric concentration of carbon dioxide up to 2010 with a threshold concentration range that is based on a 50% probability (more likely than not) of exceeding a 2°C temperature increase, given different models and scenarios (EEA 2012).

2.2.1.1 *Planck responses and feedbacks*

An increase in the global mean temperature will create positive and negative climate change feedbacks (i.e. GHGs and Planck responses) (Bony et al. 2006; IPCC WG1 5AR 2013a). Planck negative feedback is described by the Stefan Boltzmann law (the radiative emission of a body is dependent on the 4th power of its temperature) and by it Earth atmosphere would be warmer by 0.5°C to 1.3°C, given a doubling of CO_2 concentrations. However there are other positive feedbacks that have an additional impact on temperature increase (Bony et al. 2006). Water vapour is the most abundant GHG, and has a positive climate feedback on the global temperatures. Higher temperatures will cause more evaporation from the hydrosphere and cryosphere creating more water vapour in the atmosphere, causing a further increase in global temperatures (Wigley and Raper 2001; Davidson and Janssens 2006; Solomon et al. 2010). Positive climate change feedbacks are visible through changes in the other GHGs, such as CO_2 and CH_4 (Luo 2007).

Increased emissions of anthropogenic CO_2 will eventually increase global temperature further and this will affect natural reservoirs of CO_2 (e.g. land and oceans) (Cox et al. 2000; Friedlingstein et al. 2003; Luo 2007). Higher atmospheric CO_2 concentrations can work in two ways: 1) photosynthesis in some plant species will increase leading to an increase of carbon terrestrial storage; 2) temperature increase will cause the opposite effect and magnify soil respiration, turning the main terrestrial CO_2 sinks into a source (Cramer et al. 2001; Berthelot et al. 2002). Even with an increased growth in C3 plant species, with projections of higher rates of $CO_{2,}$, Cox et al.(2000), suggests that the resulting increase in temperature can lead to drying in the tropics. In Cox et al's (2000) study the impact would be a reduction in the size of the tropical Amazonian forest, and a weakened terrestrial carbon sink (Zhao and Running 2010). However, the largest emission of terrestrial CO_2 in the 21st century is expected to be from soil (Cox et al. 2000; Zhao and Running 2010). Positive CO_2 feedback and an increase in temperatures can lead to further ocean freshening and reduce vertical mixing through thermohaline circulation (Crueger et al. 2008), which leads to higher dissolving rates of CO_2 at the regional and local scale (Fung et al. 2005; Marsh et al. 2007). Methane climate change feedback will be caused by further emissions, due to permafrost melting, and thawing lakes in high northern latitudes (Walter et al. 2006; Mastepanov et al. 2008).

Changes in the Earth's albedo (reflection ability of the surface), is responsible for another positive feedback. For example, cryosphere albedo (from snow and ice), has the highest rates and reflects incoming radiation, however, with further ice/snow melt less shortwave radiation will be reflected into space, leading to an additional increase in temperature at higher latitudes, which will again contribute to the global temperature increase. This increase in temperatures is especially visible in the Arctic, where temperature increase is higher than global or Northern Hemisphere temperature increase and this is known as Arctic amplification (Serreze and Barry 2011). A key driver of this phenomenon is albedo feedback as with sea ice melt and land ice melt more dark water/land is exposed and absorbing solar radiation and increasing a temperature in the region (Serreze and Barry 2011). As relief is in 3D, quantitative measurement of albedo is not affected only by an image or type of surface but also by the orientation (Boyaci et al. 2003). These positive feedbacks can turn the present natural GHG sinks (e.g. tundra, forest, wetland, peatland, permafrost and oceans) into emission sources (Cox et al. 2000; Schuur et al. 2008; Hoc et al. 2009) and this sinks emission uncertainty is one of the largest in climate change projections.

2.2.2 Climate change impacts

Increasing attention is being focused on the impacts of climate change on natural systems and how society can best manage and adapt to these changes. This PhD project is focused on the impacts of changes in temperature, precipitation and extreme events in South West England (West Cornwall) and its effect on vegetation. It aims to provide an increased understanding of these climate change impacts locally and regionally and provide better knowledge for policy makers. The following paragraph will give insight into large scale to regional scale research conducted on temperature, precipitation and extreme events variability as a result of anthropogenic climate change.

2.2.2.1 *Temperature*

Palaeoclimatic research uses palaeo proxies for analysis of climate until the post-industrial period when climate change analyses are mainly based on instrumental weather records and these are routinely available from 19th century (Mann et al. 2008; Mann et al. 2009; Bradley 2015). In order to reconstruct past temperature changes and to assess the nature, scale and extent of post-industrial temperature variations research has focused on analysing temperature changes over a variety of timescales and regions using a range of temperature proxy data, such as tree rings, ice cores, corals, lake sediments and peat archives (Mann et al. 2008; Bradley 2015). Reconstruction of the last 2000 years of global temperature fluctuations showed that both the Little Ice Age (~1550-1850AD) and the Medieval Warm Period (~950-1250AD) were not regionally uniform and not globally pronounced (Wanner et al. 2008; Ahmed et al. 2013; Neukom et al. 2014). Furthermore, the regional temperature increase detected during the Medieval Warm Period was lower than the late 20th and early 21st centuries and is explained by natural climate variability (Mann et al. 2008; Wanner et al. 2008; Goosse et al. 2012; Bothe et al. 2013). Analysis on palaeo temperature proxies from both Hemispheres, showed warming periods over the past 1000 years have not been globally synchronous until the warming observed in recent decades (Mann et al. 2009; Neukom et al. 2014). Palaeoclimatic research use palaeo proxies for climate analysis where, post-industrial climate change analyses are mainly based on instrumental weather records, mostly available from 19th century (Mann et al. 2008; Mann et al. 2009; Bradley 2015). Analysis of 20th and 21st centuries global temperature change has shown that the increase has been greater over the land mass than the oceans, and therefore greater over the Northern Hemisphere (New et al. 2011; Kang and Seager 2012). As there are more available records of the temperature change in the Northern Hemisphere, more research has been directed towards trend detection and attribution in temperature change, and understanding of how 20th and 21st century increases could be placed in the historical context of temperature variability (Fig. 4) (Peterson and Vose 1997; Crowley 2000; Hegerl et al. 2007; Neukom et al. 2014). As well as the increase in global temperature, analysis of centennial records for the Northern Hemisphere (annual mean temperature), showed an unprecedented increase for the last decades of the 20th century; and it is estimated that only 20-25% of this can be attributed to natural climate variability (Crowley 2000) (Fig. 4).

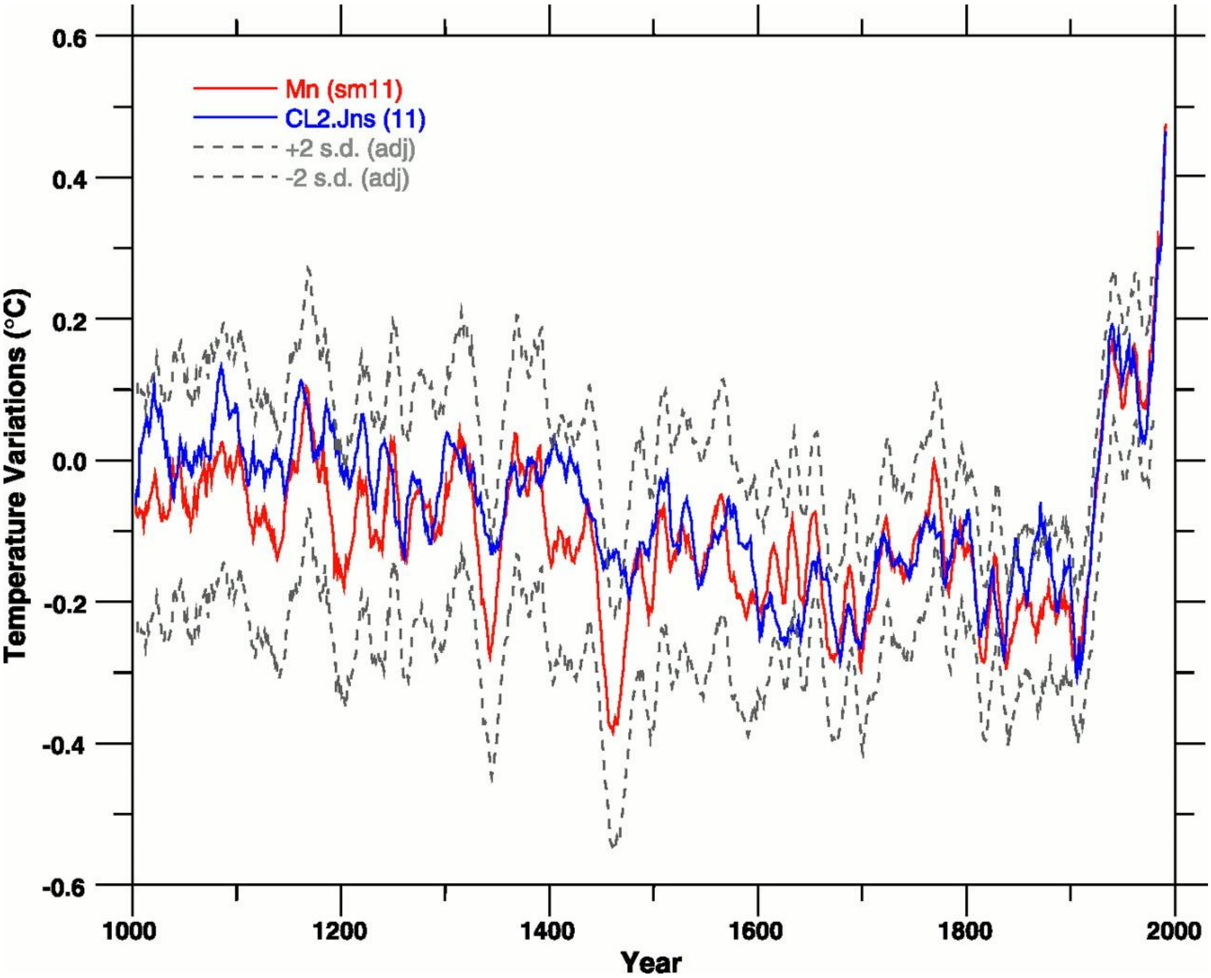


Figure 4 Northern Hemisphere temperatures change on a centennial scale. Comparison of decadal, smoothed Northern Hemisphere annual mean temperature records for the past millennium (1000-1993) based on two different (Mn and CLS) reconstructions, showing a large increase in last decades of 20th century (Crowley 2000).

As previous palaeoclimatic studies showed that temperature increase was not uniform regionally, to begin to understand the extent to which global temperature increases of 20th and 21st centuries varies regionally or locally; extensive research on regional temperature change started in the 1990s (after the first IPCC report) using instrumental weather records (Nanni et al. 1998; Brunetti et al. 2000b; Zhang et al. 2000; Domonkos and Tar 2003; Bartolini et al. 2008; Gobiet et al. 2014). Such research on temperature variability was focused on maximum, minimum, annual and seasonal temperatures, and diurnal temperature range (DTR), (DTR is defined as the difference between daily maximum and minimum temperature), analysis (Karl et al. 1993; Brunetti et al. 2000a; Zhang et al. 2000; Alexander et al. 2006a). For example Colombo et al. (2007) analysed temperature increases between 1961-2000 from 50 Italian stations and detected an increase of summer temperatures (post 1980s) with a higher increase in mountain stations, where the warming was also prolonged in the autumn season. In Norway annual temperature increases were detected in the post 1970 period, with a higher seasonal trend detected for the winter season (Hanssen-Bauer and Førland 2000). Consistent results were reported by The European Environmental Agency, showing that warming in the past 30 years over Scandinavia was the strongest in winter, whereas over the Iberian Peninsula the highest increase in temperature was detected for the summer season (EEA 2012). Some studies analysed 20th century DTR data over the United States and Canada, and detected a decreasing trend in summer and early autumn DTR (Karl et al. 1993; Zhang et al. 2000). This can be explained by greater warming in minimum temperature (Karl et al. 1993; Zhang et al. 2000). Nevertheless, the magnitude of temperature trends will vary regionally and locally and there is a need for more studies on the pattern and timing of regional and local climate change wherever instrumental data are available (EEA 2012). It has been projected that warming over Europe will be between 2.5-4.0°C by the end of 21st century with major regional and seasonal differences (EEA 2012). The seasonal increase will be the highest in the winter season over eastern and northern Europe, whereas for southern Europe the highest increase is projected to be in summer (EEA 2012).

2.2.2.2 *Precipitation*

Precipitation plays a crucial role in the climate system as well as in natural systems (e.g. cell functioning, soil formation) and social systems (e.g. water supply, agriculture, energy production, tourism) (EEA 2012), and therefore it is important to understand and detect past and present changes. Due to the nature of precipitation and its high spatial and temporal variability, knowledge of palaeo precipitation changes is quite limited and restricted to the regional scale (Liu et al. 2013). Yet, the studies that have analysed changes in palaeo precipitation, confirmed high spatial and temporal variability of precipitation (Wanner et al. 2008). Similarly to palaeo temperature change, precipitation changes during the past millennium have been attributed to natural variability (Wanner et al. 2008). In contrast to this, some recent changes in precipitation are likely driven by anthropogenic GHGs emissions (Zhang et al. 2007; Lambert et al. 2008; Allen et al. 2009).

For post-industrial era (post- 1800), it has been detected that Northern Hemisphere, mid-latitude, precipitation has been increasing since the 1950s (Dore 2005; Pauling et al. 2006; IPCC WG1 5AR 2013a), however, this increase has not been uniform throughout the Northern Hemisphere. For example; an increase in annual precipitation (post 1950s) was detected for northern Europe, whereas it was the opposite for the Mediterranean, central and eastern Europe (IPCC WG1 4AR 2007; EEA 2012). An increasing trend in winter precipitation was detected for northern, central and western Europe, whereas an increasing trend for summer precipitation was detected in central and western Europe. However, northern regions experienced drier summers (Moberg and Jones 2005). Trends in precipitation are more variable regionally and locally than globally, and assessment of this variability requires more small-scale (e.g. regional and local) research than has been carried out so far (Buffoni et al. 1999; Soden 2000; Allen and Ingram 2002; Begert et al. 2005; IPCC WG1 4AR 2007). Several studies have looked at the impact of regional and local precipitation on geophysical processes, ecosystems and the economy (Milly et al. 2005; IPCC WG1 4AR 2007). As with research on temperature, research on precipitation has concentrated on the assessment of total precipitation, annual and seasonal precipitation averages.

For example, Brunetti et al. (2000b) analysed monthly and seasonal precipitation between 1866-1995 for north and south Italian regions, and precipitation decrease was detected over the southern region where for the north region an increase was detected in winter. Buffoni et al. (1999) also analysed precipitation change over the Italian peninsula, and detected a decrease in summer precipitation for central and southern regions, as well as a decrease in autumn precipitation for the northern region. Another example of high spatial precipitation variability, has been shown over the southern and northern regions of the Iberian Peninsula, where a decreasing trend for total precipitation was detected in all seasons except autumn (Rodrigo and Trigo 2007). Different results were detected locally, showing an increasing trend in winter precipitation over the eastern Iberian coast and increasing trend in summer precipitation over inland areas of the Iberian Peninsula (Mosmann et al. 2004; Gonzalez-Hidalgo et al. 2009). Projections for the 21st century indicate a general increase in precipitation for northern Europe and a decrease for southern Europe (Portmann et al. 2012).

Furthermore, a decrease in summer precipitation will be most prominent in southern Europe, but also visible in central and north western Europe (Tapiador 2009).

All of this research on precipitation shows a high spatial and temporal variability of precipitation over Europe, justifying a need for more extensive regional and local research, as the impacts on ecosystem and society will depend on the magnitude and direction of local and regional precipitation change.

2.2.2.3 *Extreme events*

An extreme weather or climate event can have a devastating impact on society and the natural environment, causing loss of life, illnesses and increase in economic costs (Katz and Brown 1992; Easterling et al. 2000a; Christidis et al. 2005; Patz et al. 2005; Loarie et al. 2009; IPCC WG1 5AR 2013a). There are several ways that extreme events can be measured and defined: by percentile indices (above 90th or 95th percentile in a distribution), by absolute indices (counts of days crossing a specified absolute value), by analysing data above a threshold (partial duration series) or by modelling the heavy tails of the distributions (Frich et al. 2002; Klein Tank and Können 2003; Kunkel et al. 2003; Alexander et al. 2006b).

Extreme events are typically rare, however it has been suggested that with anthropogenic climate change they will increase in their magnitude, duration and frequency (Giorgi and Mearns 1991; Giorgi and Lionello 2008; Orlowsky and Seneviratne 2012; Zwiers et al. 2013; Herring et al. 2014). Furthermore, it has been suggested that extreme events can be divided into two groups: extreme changes in daily/monthly temperature or precipitation, and extreme driven events such as floods, increased run-off, droughts, heat-waves and wind-storms (Easterling et al. 2000b; Schar et al. 2004; Trenberth 2011). Analysis and prediction of extreme events are important issues that scientists are trying to address on regional scales, as their impact is mostly visible regionally and locally and is spatially highly variable (Frich et al. 2002; Luterbacher et al. 2004b; Ekström et al. 2005; Bartolini et al. 2008; Giorgi and Lionello 2008), however, due to high spatial variability, extreme precipitation predictions are more ambiguous than temperature extremes (Orlowsky and Seneviratne 2012). Since the 1950s an increasing occurrence of extreme heat waves has been detected in the Northern Hemisphere (Beniston et al. 2007). More extreme heat waves over Europe have been recorded since the 1970s, with two severe heat waves in the summers of 2003 and 2006, which resulted in increased death rates (i.e. France and Italy) (Beniston 2004; Beniston and Stephenson 2004; Kovats and Kristie 2006; Fouillet et al. 2008). Furthermore, the later heat waves caused droughts which led to crop failure and had big impacts on European food production (EEA 2012). Cold winter days and spells such as in the winters 2005-2006 over England and Wales and winters in 2009-2010 over Northern Europe and Eastern United States also increased mortality rates (Hajat et al. 2007; Cattiaux et al. 2010; Wang et al. 2010). Studies on precipitation extreme events showed an increase in days where the precipitation value exceeded the 95th percentile, and in their frequency over most European land areas and this increase was more pronounced in autumn and winter seasons (Klein Tank and Können 2003; Zolina et al. 2004; Kundzewicz et al. 2012; Chen et al. 2014). Such extreme precipitation caused historically severe floods over Europe (Frei et al. 2000; Kundzewicz et al. 2012). For example, in 1997 and 2002 severe floods occurred in central and southern Europe (Christensen and Christensen 2003; Mudelsee et al. 2003; Christensen and Christensen 2004), and these have been linked with locally higher storminess and high wind speed, which are usually accompanied with high precipitation (Kunkel 2003; Keim et al. 2004; EEA 2012; Kundzewicz et al. 2012). Some studies have suggested that storminess has increased across north-west Europe in the period from 1871 to 2008, whereas others showed a decrease in storminess since 1990s (Wang et al. 2011; EEA 2012). Pryor et al. (2012) showed that extreme wind will increase in Northern Europe by the end of 21st century, however this could vary regionally. Nevertheless, floods in Europe can be driven by different factors in different regions. For example, floods in the Atlantic region have resulted from extreme precipitation, but also resulted from the increased storminess, higher waves and storm surges (The Wasa Group 1998; Collier and Fox 2003; Lozano et al. 2004; Donat et al. 2010), whereas in the Mediterranean and Alps regions, floods are more dependent on the seasonal precipitation peak (Mudelsee et al. 2003; Marchi et al. 2010). Furthermore, an increased precipitation can also trigger other extreme events such as increased run off and landslides (Frei et al. 2000; Guzzetti et al. 2007). Such extreme events as floods or landslides can exacerbate infectious diseases through pathogens in ground water and cause mental health problems (Hajat et al. 2005; Berry et al. 2010). Understanding the patterns of previous extreme events can help in future projections and minimise economic and social losses (Fowler and Kilsby 2003;

Berry et al. 2010), however extreme events projections are still challenging task due to high spatial and temporal heterogeneity of these events and lack of daily instrumental data (Zwiers et al. 2013).

Extreme temperature events account for both, warm and cold days, however studies showed that the latter are becoming less frequent over Europe (Chen et al. 2014). Extremes in high temperatures are predicted to increase in their length and frequency over the whole of Europe, but will be more pronounced over the Mediterranean region (Chen et al. 2014). The largest increase will be in very extreme high daytime temperatures (over 35°C) and night temperatures (Fischer and Schar 2010; Seneviratne et al. 2014). Precipitation projections suggest that the Mediterranean region will be drier by the end of the 21st century, whereas northern Europe will have more heavy precipitation (Boberg et al. 2010), however other studies showed a decrease in heavy precipitation events which suggests a large regional differences and therefore it is essential to undertake more regional and local studies (Rodda et al. 2010; Chen et al. 2014). Future dry periods have been associated with the summer season for most of Europe, and this will have a large impact on water supply, as well as water demand, due to increased irrigation (Keirle and Hayes 2007), whereas increased winter precipitation is projected for northern Europe (EEA 2012). An increase in storminess has been projected for ‘high impact’ storms and extreme wind speeds over northern Europe, whereas wind speed should decrease over southern Europe (EEA 2012; Pryor et al. 2012). It has been projected that heavy precipitation and increased storminess will increase the frequency of flash and pluvial floods throughout Europe (Kundzewicz et al. 2006; EEA 2012).

2.2.2.4 *NAO index and its impact on climate and ecosystems*

Several atmospheric teleconnections cyclic patterns such as Atlantic Multidecadal Oscillation (AMO), Pacific North American Pattern (PNA) and Arctic Oscillation (AO) have an impact on Northern Hemispheric climate (Schaefer et al. 2005; Feldstein and Franzke 2006; Knight et al. 2006; L'Heureux et al. 2008; Hurrell and Deser 2009b; Trouet and Taylor 2010). However, the North Atlantic Oscillation (NAO) has been the dominant circulation pattern, which affects annual and seasonal changes in temperature and precipitation, particularly over the eastern United States, Europe and the UK

(Hurrell 1995; Hurrell and Van Loon 1997; Thompson and Wallace 2001; Knight et al. 2005; Feldstein and Franzke 2006; Knight et al. 2006; Hurrell and Deser 2009b; Liu et al. 2012; Olsen et al. 2012). The NAO index reflects the pressure difference between the Icelandic low pressure and the Azores high pressure regions, and is defined by its positive or negative index, which controls the strength and direction of westerly winds (Hurrell 1996; Hurrell et al. 2003). Studies analysing NAO index variability on a millennial scale showed that it had an important control in European climate and the onset of the Little Ice Age (~1550-1850AD) was linked with a change to the negative NAO mode, however this was opposite to the onset of the Medieval Warm Period (~950-1250AD) which was not linked with a change to a positive NAO mode (Proctor et al. 2000; Cook et al. 2002; Olsen et al. 2012). Other studies showed that the NAO index was in its positive mode during the Medieval Warm Period, however the actual shift between NAO modes happened 1000 years prior to the beginning of Medieval Warm Period (Trouet et al. 2009; Olsen et al. 2012). Moreover, it has been suggested that transitions between the Little Ice Age and the Medieval Warm Period, while NAO index was negative, could be linked to the weakening of the Atlantic Meridional Overturning Circulation (Denton and Broecker 2008; Trouet et al. 2012).

Recently, it has been shown that changes in the 20th and 21st century's NAO index can be associated with a variability in the strength and latitudinal shifts of eddy (i.e. momentum flux convergence by atmospheric waves) driven North Atlantic jet stream, and the widening of the Hadley cell which was noticeable in recent decades and driven by anthropogenic climate change (Johanson and Fu 2009; Li and Wettstein 2011; Woollings and Blackburn 2011; Ceppi and Hartmann 2012).The NAO index was largely positive (between the mid-1960s to mid-1990s) and negative, (from mid-1990s) (Hurrell and Deser 2009b; Jung et al. 2011). There are two types of NAO indices, the Station based and the Principal component (PC) NAO index, and they have been created in response to a growing interest in analysing the correlation of these indices with climate records over the Northern Hemisphere (Raible et al. 2013).

The station based NAO index is calculated from instrumental sea level pressure (SLP) records from Lisbon, Portugal and Stykkisholmur/Reykjavik. The PC NAO index is calculated by the empirical orthogonal function of SLP anomalies over the Atlantic sector (i.e. 20°-80°N; 90°W-40°E). The key strength of station based data is that the NAO index is available from 1820; the key weakness is that the station based records are fixed in space and unable to follow the NAO centres on their annual cycle over the Atlantic region. For the PC based index, the key strength is that it better represents the movement of the NAO centres which reduces the noise in the data, however the key weakness is that the PC index is only available from 1899 and represents only monthly and yearly data, depending on the availability of the data and gridding scale (Hurrell 2012). Depending on timescales and data, different studies use different NAO indices for their analysis.

The NAO index has a strong influence on temperatures over Europe, and a positive correlation has been detected between its positive mode and warmer than average northern European winters, whilst there is the opposite impact during the negative mode of the NAO index, and lower than average winter temperatures (Beranová and Huth 2007; Pinto and Raible 2012). The same pattern was detected for winter season maximum temperatures over Central Europe, the Iberian Peninsula and the Balkan region; however no positive correlation was detected between minimum temperatures and the NAO index (Trigo et al. 2002).

Studies on the relationship between the NAO index and Northern Hemisphere precipitation have detected a positive correlation (Hurrell et al. 2003; Hurrell and Deser 2009b), and established that during periods with a positive NAO index, Northern Hemisphere (western Europe) winters experience periods of predominant westerly winds, associated with heightened storminess and high precipitation rates (Hurrell 1996; Hurrell and Van Loon 1997; Hurrell and Deser 2009b). A decrease in precipitation rates in winter is characteristic for Mediterranean Europe during positive phases of the NAO index (Cullen et al. 2002; Trigo et al. 2002; Muñoz-Díaz and Rodrigo 2004), however there were regional exceptions to this rule with an increase in winter precipitation over the south coast of the eastern Mediterranean, between southern Israel and Libya (Dünkeloh and Jacobeit 2003). During negative phases of the NAO a different pattern was detected for northern and central Europe showing an increase in winter precipitation, where this was opposite for southern Europe and the Mediterranean showing a decrease in winter precipitation (Dünkeloh and Jacobeit 2003; Muñoz-Díaz and Rodrigo 2004; Rodrigo and Trigo 2007). In order to make projections of future NAO variability and better understand its impact on regional and local climate, it is necessary to better understand the mechanisms that affect the NAO index (e.g. sea surface temperature, changes in GHGs) (Proctor et al. 2000; Proctor et al. 2002; Hurrell and Deser 2009b; Olsen et al. 2012). A more detailed discussion of the NAO index and its correlation to temperature and precipitation over West Cornwall will be addressed in Chapter 4.

Some studies analysed the impact of the NAO on ecosystems as it has been suggested that changes in the NAO pattern explains the biodiversity response to climate change better than global weather data, as ecosystems do not respond to single climate variables (e.g. temperature or precipitation), and teleconnections can better present a local climate variability (Stenseth et al. 2003). However, this might not be the case if local weather data are available. Nevertheless, there have been several studies investigating phenological changes associated with the NAO index. For example, a study by Chmielewski and Rötzer (2001) investigated the correlation between the NAO index and tree phenological changes over Europe, in the period 1969–1998, and detected a positive correlation with a positive mode of NAO (i.e. warmer winter and early spring temperatures) and earlier vegetation growing season. Studies that analysed changes in seasonal phenological events in plants throughout Germany or changes in vertebrate population dynamics in Greenland detected a positive correlation with NAO index (Post and Forchhammer 2002; Menzel 2003).

2.3 Global scale climate change impacts on biodiversity

The impact of the recent climate change on biodiversity has been studied in various ways; by analysing changes in phenology, changes in species geographical distribution, species extinction, intrusions of invasive species and higher and lower growing rates for C3 and C4 plant type species in response to increased levels of CO_2 (Mann and Bradley 1999; Walther et al. 2002; Gurevitch and Padilla 2004; Parmesan 2006; Worm et al. 2006; Parmesan et al. 2011). Climate change impacts on biodiversity can be divided into direct or indirect; direct impacts are related to temperature and precipitation change, affecting changes in the life cycle (phenology), extinction, changes in the geographical distribution of species and subsequently, changes in population genetic diversity (Woodward and McKee 1991; Woodward 1993; Cao and Woodward 1998; Parmesan 2006; Bertin 2008; Beaumont et al. 2011; Moritz and Agudo 2013). The indirect impacts are observed through wider changes in ecosystem function (e.g. changes in the food chain or in dispersal rates of seed and pollen) and this can lead to changes in ecosystem composition (Davis and Shaw 2001; Bale et al. 2002; Edwards and Richardson 2004). This section will provide an insight into previous research carried out on biodiversity response to climate change.

2.3.1 Phenological change as proxies for climate variability

Phenology analyses annual changes in life cycle events of animals and plants, such as timing of migration, of egg hatching or of flowering and fruiting (Fitter and Fitter 2002; Root et al. 2003; Rosenzweig et al. 2008). Studies on phenological cycles in plants mostly analysed the changes in flowering and fruiting, and fewer studies have assessed the changes in length of flowering season (Fitter and Fitter 2002; Menzel et al. 2006a; Dunnell and Travers 2011). Recent studies have suggested that long term phenological changes can be a good proxy for climate change detection (e.g. temperature change), at the regional or local scale as seasonal vegetative activities depend on temperature and precipitation changes (Walther et al. 2002; Parmesan 2006; Ibanez et al. 2010; Cook et al. 2012; Panchen et al. 2012; Calinger et al. 2013). Studies that were conducted worldwide, using herbarium data or photographs of vascular plants, showed phenological changes in the past 40-60 years (Mann and Bradley 1999; Walther et al. 2002; Primack et al. 2004; Miller-Rushing et al. 2006; Parmesan 2006; Schwartz et al. 2006; Robbirt et al. 2011). Although phenological changes can clearly happen in response to natural variation or to non-climatic factors (e.g. genetic variation or plant to plant interaction, or plant-pollinator interaction), recent studies show that changes in the 20th and 21st century can be related to the post-industrial climate change (Walkovszky 1998; Hughes 2000; Badeck et al. 2004; Wolfe et al. 2005; Menzel et al. 2006a; Parmesan 2006; Elzinga et al. 2007; Kauserud et al. 2008; Miller-Rushing et al. 2008; Neil et al. 2010).

Research on climate change and phenological impacts has been focused at regional and local scales, however the key problem in conducting this type of research comes from the absence of complete long term, historical records (i.e. herbarium records and photographs) with flowering dates (Lavoie and Lachance 2006; Gallagher et al. 2009; Robbirt et al. 2011; Panchen et al. 2012; Calinger et al. 2013; Lavoie 2013). Numerous studies, analysing phenological changes over the Northern Hemisphere used historical data sets and revealed earlier flowering trends by the end of 20th century, however there are fewer studies analysing the changes in the length of flowering (Menzel et al. 2006b; Bock et al. 2014). For example, Parmesan at al. (2007) preformed a meta-analysis on 203 species across all taxa and found that a phenological response in the Northern Hemisphere will be in advance of spring events, on average between 2.3 and 2.8 days decade^{-1}. Another study, analysed 542 plant species from 21 European countries and detected earlier flowering on average by 2.5 days decade^{-1} in the period between 1971-2000 (Menzel et al. 2006a). These changes are not uniform and varying regionally and locally, due to the differences in temperature change, and between species (Peñuelas et al. 2002; Parmesan 2007; Nordli et al. 2008; Črepinšek et al. 2012).

In order to detect changes in phenology and link it with recent climate change, it is necessary to take into consideration changes in the geographical distribution of plant species, their local geography (latitude and elevation) as well as changes in urbanised areas, as all this can influence temperature (Ahas et al. 2002; Parmesan 2007; Neil et al. 2010). Changes in a phenological cycle are one of the essential biodiversity responses to climate change, having an impact on ecosystem functioning and productivity (Menzel et al. 2006b; EEA 2012). Bock et al (2014) suggested that more studies should analyse changes in the length of flowering, and not just in the date of flowering, as this can impact human health (due to the longer exposure to allergenic pollen) and cultural ecosystem service (Sakurai et al. 2011; Ziello et al. 2012; Hoye et al. 2013). The scope of this PhD research will not be to identify changes in vegetation phenology; however it will use historical vegetation datasets to detect changes in the geographic distribution of vegetation in west Cornwall. Currently there are more studies using historical data to detect changes in phenology than in changes of geographic distribution of plant species (Bertin 2008) particularly at regional and local scales and therefore this project will try to begin to fill this gap.

2.3.2 Geographical shifts in species distribution

Plant species have shown the ability to adapt to climate change. However, the present rate and nature of climate change and habitat fragmentation are reducing this adaptive ability (Jump and Peñuelas 2005; Jump et al. 2006; Parmesan 2006; Loarie et al. 2009), causing species to follow the climatic envelope, which will lead to changes in the geographical distribution of biodiversity (Davis and Shaw 2001; Walther et al. 2002; Skov and Svenning 2004; Parmesan 2006).

Recent research has shown that some vegetation species changed their geographic range during the 20th and this change has been associated with the global temperature increase over this time (Parmesan et al. 2000; Walther et al. 2002; Parmesan and Yohe 2003; Parmesan et al. 2011). The main direction of this change was towards higher elevations and higher latitudes (Grabherr et al. 1994; Hughes 2000; Walther et al. 2002; Thomas et al. 2004; Thuiller et al. 2005b). Globally, longitudinal changes of species geographic distributions were measured by 6.1km per decade, where those shifts in the Northern Hemisphere measured 16.9km per decade where altitudinal changes were on average 11 m per decade (Parmesan and Yohe 2003; Chen et al. 2011). A study of 171 forest plant species in western Europe, analysed their change over the 20th century and detected an altitudinal shift of 29 meters per decade (Lenoir et al. 2008). Research on vegetation change in the Swiss Alps, ‘Biodiversity Monitoring Switzerland’ showed an altitudinal shift was 13 meters per decade (Hintermann et al. 2010). An emphasis in current research in vegetation is to detect whether species restricted to the mountain areas are more susceptible to the changes in geographic distribution due to regional and local climate change (Thuiller et al. 2005b; Parmesan 2006; Lenoir et al. 2008; Thuiller et al. 2008). This is important as mountain species have less available ‘space’ to move than lowland species, and are restricted to microclimates in order to persist locally and regionally (Spehn et al. 2010; Scherrer and Körner 2011). However, the ability of species to move will also depend on: habitat disturbance, man-made barriers and local availability of ‘new micro-habitats’. This focuses the need for more small scale based research (regional/local) as biodiversity response to climate change will depend on the climate change magnitude at the small scale and on the climate sensitivity of individual species, and their tolerance towards abiotic changes in the environment. This will be explained in greater detail in Chapter 5.

2.3.3 Species extinction

Currently, species are facing a very high risk of extinction from present and future climate change, and the most vulnerable species are those within limited geographical areas and without the opportunity or ability to move to higher elevations or latitudes (e.g. islands or mountain areas), species with lower adaptive capacity (i.e. low genetic diversity), and species whose migration would be limited by man-made barriers and habitat fragmentation (Gottfried et al. 1999; Parmesan and Yohe 2003; Walker et al. 2006; Pauli et al. 2007; Bellard et al. 2012). Palaeo research showed that most of the species successfully shifted their ranges as a response to the previous climate change (Pardi and Smith 2012; Corlett and Westcott 2013; Ordonez and Williams 2013). However, the situation nowadays is very different, as the velocity of climate change is expected to increase by the end of 21st century and other pressures on ecosystems are increasing as well (e.g. changes in land use) (Loarie et al. 2009; Ordonez et al. 2014; SCBD 2014). This will lead to much more fragmented habitats than in the pre-industrial era and therefore it will be more difficult for species to migrate (Ewers and Didham 2006; Loarie et al. 2009). More fragmented habitats can increase local extinctions, as gene flow, with better adapted populations is disrupted, and this leads to a lower level of genetic diversity and a lower evolutionary potential (McKay et al. 2005; Aguilar et al. 2008; Corlett and Westcott 2013). It was suggested that mitigation lag could be a possible response to climate change, yet the evidence showed that the velocity of climate change might be too high for species to adapt quickly (Devictor et al. 2008; Harrison and Sanchez Goñi 2010; Ordonez et al. 2014). In addition, the velocity of climate change will vary regionally and reaction to it will be species dependent (e.g. exposure to climate change, climate sensitivity of particular species, ability to acclimatise and ability to adapt) and will affect and minimise species resilience to the change (Redman and Kinzig 2003; Folke 2006; Gallopín 2006; Dearing 2008; Corlett and Westcott 2013). Ecosystem resilience has been discussed throughout the literature, more in a theoretical than a practical way, and there are still many gaps in knowledge of how an ecosystem will respond, depending on which species are lost, local connectivity and genetic diversity (Nyström et al. 2008). Hence, there are still a lot of unknowns on the ability of species to adapt and acclimatise to climate change and in that way minimise extinctions (Savolainen et al. 2007; Stanton-Geddes et al. 2012; Corlett and Westcott 2013). Recent studies such as Global Living Index (measuring trends in

10,380 populations over 3,038 of vertebrate species), showed a decrease for 52 % of species between 1970 and 2010 (WWF 2014). Global projections estimate that by the end of the 2050s 15-37% of plant species will be in danger of extinction due to climate change (Thomas et al. 2004; IPCC WR2 4AR 2007; Moritz and Agudo 2013). Furthermore, it has been suggested that 35-55% of European alpine plant species will lose 80% of their range by the end of the 21st century (EEA 2012), and this might increase their risk of further extinction, predicted to be ≈ 60% by 2080 (Thuiller et al. 2005b). The European mid-latitude region is expected to experience reduced species loss and more alien species intrusions than other regions; although this masks considerable small-scale variability (Lavergne and Molofsky 2007). Besides anthropogenic pressures on ecosystems, species extinction could also depend on invasive plant species intrusions and infectious disease (Smith et al. 2006; Rands et al. 2010; WWF 2014).

However, it has been shown that invasive plant species intrusions might not have a direct key role in species extinction (Gurevitch and Padilla 2004; Didham et al. 2005; Smith et al. 2006). Invasive plant species use environmental change as an advantage and therefore they act more as a response to the environmental change than a driver of change in ecosystem composition (Didham et al. 2005). Other research has shown that the success of an invasive plant species depends on the diversity of native plant species, as well as the magnitude of genetic variance within invasive plant species populations (Lee 2002; Kinziger et al. 2011). Nevertheless, there are still questions that need to be answered regarding invasive plant species intrusions. Most studies compare invasive and non-invasive plant species, however it has to be taken into account that some natives could be very successful (Pyšek and Richardson 2007; Van Kleunen et al. 2010). On the other hand fewer studies analyse which invasive plant species are more successful than others, and why less successful species fail to establish. To fully understand the impact of the invasive plant species on native plant communities it is necessary to assess which traits of invasive plant species (e.g. climatic range, phenotypic plasticity, dispersibility) are important for which invasive stage and on which spatial scale (Van Kleunen et al. 2014). Furthermore, beside climate change impacts, invasive plant species intrusion will be dependent on the presence of the appropriate environment and the species ability to move to this ‘new’ environment, which is altered by anthropogenic impact (Pyšek et al. 2010; Van Kleunen et al. 2014). Hence, more research is needed on the relation between climate change, vegetation loss, and invasive plant species intrusions (MacDougall and Turkington 2005), as these intrusions are becoming a threat to biodiversity at the global, regional and local scale, causing economic costs and health problems, and presenting an ongoing challenge for conservation and policy makers (Gurevitch and Padilla 2004; Pimentel et al. 2005).

This PhD research will not investigate invasive plant species intrusions in West Cornwall as this is beyond the scope of this research project. However, it is important to acknowledge that invasive species intrusions might affect ecosystem compositions and ecosystem functioning and therefore decrease the genetic diversity of native plant species, leading to the higher extinction rates (Hooper et al. 2005; MEA 2005; Lavergne and Molofsky 2007). The Convention on Biological Diversity published a strategic plan on how to prevent and mitigate the further loss of biodiversity in 21st (SCBD 2014). Loss of plant species in West Cornwall will be discussed further in Chapter 6.

2.3.4 Species with different photosynthesis pathway

Anthropogenic influence on climate, and an increase in CO_2, will impact plant species, photosynthesis, and consequently, their growth (Idso et al. 1987; Wray and Strain 1987; Tissue et al. 1997; Hughes 2000; Taylor et al. 2011). There are two different pathways of photosynthesis, defined by the categories C3 and C4 plant species. C3 plant species (e.g. shrubs) have the photosynthetic carbon reduction cycle (PCR) photosynthesis pathway, which has one chloroplast type and photosynthesis is completed in one cell where the enzyme rubisco is responsible for the uptake of CO_2. Under low levels of CO_2 rubisco will use O_2 from the cell and slow down photosynthesis. This sensitivity of the enzyme rubisco towards O_2/CO_2 uptake will lead to a positive response of C3 species with increased atmospheric CO_2. In C4 species (e.g. grasses) photosynthesis is carried out in two cells and two chloroplasts. These species have much higher concentrations of CO_2 in the cells than in C3 species, meaning that they do not use additional atmospheric CO_2 (Furbank and Taylor 1995). Therefore, it is possible that in areas with higher atmospheric CO_2, C3 species will outgrow C4 species (Wray and Strain 1987; Woodward et al. 1991; Ehleringer and Cerling 2002).

2.3.5 Genetic diversity

Understanding how climate change can affect species and their genetic diversity is crucial for understanding ecosystem functioning and ecosystem composition. Climate change affects species by changing their geographic distribution (e.g. range reduction and range shift) (Jump and Peñuelas 2005; Parmesan 2006), and this can be seen in habitat fragmentation and habitat loss, leading to a reduction in population size and bottleneck effects (sudden reduction in population size causing reduced genetic variation), (Coates 1992; Pullin 2002; Reed and Frankham 2003; Dawson et al. 2011). Smaller populations have a higher rate of loss of their genetic variation through genetic drift and inbreeding depression (Frankham 1995; Spielman et al. 2004), which leads to a reduced genetic fitness in such populations. Hence, populations with reduced genetic fitness have a minimised ability to adapt to environmental change, and are, therefore, more susceptible to extinction (O'Grady et al. 2006; Jump et al. 2009; Corlett and Westcott 2013).

Generally speaking, most of the species with a higher range loss will lose their genetic diversity, however, not all species that lose their range size will have a large loss in their genetic diversity, as this depends on distribution of genetic diversity through the entire species range and on the dispersal abilities (Aguilar et al. 2008; Jump et al. 2009). Furthermore, species that are adapted to long distance dispersal will lose less genetic diversity than the ones without that ability (Alsos et al. 2012). Nevertheless, it can be very important to understand which part of their range species are losing in cases when they do not have a uniform level of genetic diversity throughout their range (Eckert et al. 2008; Alsos et al. 2009). For example, if species have a higher genetic diversity at the southern margin of their range and lower in the northern it is very important to know what part of the range is endangered as on this will depend the magnitude of the overall loss of genetic diversity, which might lead to their extinction (Alsos et al. 2012). It is also true that extinction affecting the local scale does not immediately affect the global one, however the important question has been addressed by Cardinale et al. (2012): "How many species can we afford to lose before the functioning of the ecosystem is affected on a local scale and overall species genetic pool on a global scale?" Nevertheless, some studies have suggested that 25-50% of species in the ecosystem are needed to maintain local scale ecosystem functioning (Purvis and Hector 2000), however, this does not take into account ‘key species’, important for particular ecosystems as their loss might disrupt ecosystem functioning. Even if this is true there is the question of how long, and over which temporal and spatial scales these species will remain, and this is still unknown. Therefore, there is a clear need for more studies on genetic diversity of individual species throughout their ranges, and more local studies on changes in species geographic distributions and in their range loss. This is an extremely important first step in order to develop appropriate conservation strategies to be able preserve species and prevent the loss of ecosystem service and genetic diversity (Worm et al. 2006). The IUCN red list of endangered species, currently does not take into account species genetic diversity, meaning that species that are not on that list and do experience loss of their range could be endangered or vulnerable (Alsos et al. 2012).

2.3.6 Importance of Ellenberg values as an environmental change indicator

Ellenberg values have been used as a method to track changes of plant species in the natural environment or agricultural landscape and have been recognised as good indicators for environmental change (Hill et al. 2000; Pignatti et al. 2001; Diekmann 2003; Ernst et al. 2003; Muller 2010; Renetzeder et al. 2010; Häring et al. 2012). Ellenberg values were established to present species sensitivity to environmental elements such as: temperature (T), continentality (K), light (L), moisture (M), reaction (R), nitrogen (N) and salt (S), (Hill et al., 2000). Ellenberg values for UK plant species were given nine classes, as in the original Ellenberg system, and were re-calibrated for L-light, M-moisture R-reaction (ph soils or water) and N-nitrogen (soil fertility) (Hill et al. 2004). They were created for Central European plants and in the 1990s they were adjusted for UK plants (Hill et al. 2000; Hill et al. 2004). Hill et al. (2004), calculated the values for British plants to compare the original value of the Central European species with the mean value of the new (British species) (Godefroid and Dana 2007). For example, N=1 means that the plant requires infertile soils and N=9 means that the plant requires nutrient rich soils. Hill et al. (2004) did not believe that transporting original Central European Ellenberg values for temperature would work in the British climate. Therefore, instead of Ellenberg values for January and July, temperatures were derived from mean values of 10 grid cells where particular species live. The same derivation was performed for precipitation (Hill et al. 2004). One of the aims in this study was to examine whether Ellenberg values can be used as a link to connect changes in species geographic distribution and climate variability over West Cornwall as this has been a proposed missing link that can be employed to attribute vegetation change to climate change (Parmesan et al. 2000; Parmesan et al. 2011) and this will be further discussed in Chapter 5. The following sections will outline climate change impacts on the United Kingdoms' (UK) climate system and biodiversity.

2.3.7 Non-climatic impacts on biodiversity, land use

Previous sections explained the effect of climate change on biodiversity. However, climate change is not the only pressure that has been placed on biodiversity in the post-industrial era (Corlett and Westcott 2013; SCBD 2014). In addition, biodiversity change in 20th and 21st century has also been modified by non-climatic factors (Jetz et al. 2007; Pompe et al. 2008). These factors are altered by human impact and are visible in habitat loss or habitat fragmentation, a disturbance due to land use change (Davis and Shaw 2001; Pullin 2002; SCBD 2014). Land use change refers to changes to the natural landscape for human use or changes in management practice in agriculture (Foley et al. 2005). Furthermore, land use change is spatially and temporarily heterogeneous and depends on socioeconomic development (e.g. population, technology) geographical characteristics of the area (e.g. soil, topography) and land use history (Lambin et al. 2001; Meiyappan et al. 2014). Hence, land use change will have an impact on ecosystems which will vary on a global and regional scale, and might create positive climate feedback due to vegetation change or loss and increased CO_2 emissions (Piao et al. 2007; Locatelli et al. 2015). More extensive changes in ecosystems such as deforestation or urbanisation could also magnify a regional scale climate change (Houghton 2003; Kalnay and Cai 2003; Van der Werf et al. 2009).

Nevertheless, land use changes can be a cause of biodiversity decline and extinction, soil degradation, habitat fragmentation, and changes in ecosystem composition and functioning (Foley et al. 2005; Piao et al. 2007). The magnitude and speed of these changes differs regionally and locally but there is still lack of research on such a fine scale (e.g. depending on land use practices), and less understanding to what extent this will impact regional and local biodiversity and therefore ecosystem services provisioning (MEA 2005; Carpenter et al. 2009; Balvanera et al. 2012; Meiyappan et al. 2014; Ordonez et al. 2014). It has been known that present human population growth and the search for new ‘resources’ will have an even more diminishing effect on ecosystems and a magnifying effect on climate change (Lambin et al. 2001; MEA 2005). Therefore, a switch to sustainable land management (defined as a procedure that integrates land, water, biodiversity, and environmental management to meet food and fibre demands while sustaining ecosystem services and livelihood), is essential and a challenge for policy makers to work towards at the regional and local scale (Workd Bank 2006; Motavalli et al. 2013). It is understood that climate change is a high threat to biodiversity (Corlett and Westcott 2013; Garcia et al. 2014), yet it is still unclear to what extent biodiversity change is a result of land use change or climate change, as the speed of both varies regionally (Sala et al. 2000; Jetz et al. 2007; Cahill et al. 2013; Ordonez et al. 2014). Nevertheless, extensive land use change, plus climate change will magnify even more the pressure on biodiversity (Jetz et al. 2007; Carpenter et al. 2009; Cardinale et al. 2012; SCBD 2014). Land use change in West Cornwall is not within the scope of this study due to limited amount of time to do this research; however it is important to understand that such changes could impact biodiversity change.

2.4 The importance of historical records in climate change and biodiversity research

To be able to analyse and understand changes in the climate at the regional or local scale and biodiversity response, it is necessary to have good spatial and temporal coverage with current, but even more importantly, a good availability of historical weather and vegetation records.

Research on regional or local climate variability in the past depends on the availability of long term instrumental records locally or regionally (Domonkos and Tar 2003; Camuffo and Bertolin 2012). Most archive instrumental data sets are not in digital form and therefore they need to be assessed from archives and digitised, before any analysis can take place. This is a challenging and time consuming task because changes in measuring instruments can lead to changes in observation practices which requires careful checking throughout the data sets (Changnon and Kunkel 2006). Furthermore, changes in instruments, as well as station relocation, can show trends not related to climate variability, and therefore it is important to know if the data meets homogeneity requirements (Domonkos and Tar 2003; Begert et al. 2005; Changnon and Kunkel 2006; Colombo et al. 2007; Firat et al. 2011). The major goal of researchers today is to create globally homogenised instrumental data that are easily available to end users (Thorne et al. 2011; Chandler et al. 2012).

Assessing biodiversity change at the regional and local level also depends on the good spatial and temporal availability of historical data (Lavoie et al. 2007; Garcia-Milagros and Funk 2010; Feeley 2012; Panchen et al. 2012; Lavoie 2013; Hart et al. 2014). For example, different types of data have been used to address changes in phenology or invasive species intrusions (e.g. herbarium records, photographs), where, for changes in geographic distribution, previous research mainly uses field-based surveys, field notes, and historical museum collections (Tsutsui and Suarez 2004; Elith and Leathwick 2007; Crawford and Hoagland 2009; Gallagher et al. 2009; Neil et al. 2010; Robbirt et al. 2011). Some studies have used ‘database of herbarium records’ but such databases already include geographical coordinates and do not need manual geo-referencing (Hijmans and Spooner 2001). More information on historical data and methodology used in this study will be presented in chapter 3, 4, 5 and 6.

2.5 National importance of climate change impacts

The United Kingdom (UK) has the longest instrumental temperature record in the World; the Central England Temperature (CET) (derived from stations in English Midlands) with daily mean records that are available from 1772 and monthly mean records available from 1659 (Manley 1953; Manley 1974; Parker et al. 1992; Parker and Horton 2005). Minimum and maximum temperatures, daily and monthly data are available from 1878 (Parker et al. 1992; Parker and Horton 2005). Records show an overall increase in annual mean temperature since the 19th century, with an increase by 1°C from the 1950s, which was followed by two of the warmest decades; 1990-2000 and 2000-2010 (Jenkins et al. 2009). For the seasonal temperature change; summer temperature between 1772-2000, showed an increase of 0.67±0.26°C per century, whereas for the winter season this warming was +0.30°C per century (Brabson and Palutikof 2002). The CET record showed that the year 2006 was the warmest for the minimum temperature whereas the year 2014 was the warmest for the mean annual temperature (King et al. 2015) in the UK. A temperature increase of 0.2 °C in the last 35 years has been measured, with 1998, 2005, 2003, 2002, 2004, 2006, 2001, 1997, 1995,1999 and 2014 being the 11 warmest years (by rank order), (Jenkins et al. 2009; King et al. 2015). Furthermore, annual temperature increase was higher in southern England and lower in eastern England and Scotland (Jenkins et al. 2008). Seasonal temperature change is shown particularly through higher winter temperatures, and this correlates with a recent positive NAO index (Hurrell 1995; Hurrell and Van Loon 1997; Luterbacher et al. 2001). Increases in extreme summer temperatures mean that damaging heat waves, such as that in the summer of 1995, (Rooney et al. 1998), and in 2003, and 2006 have led to an increased human mortality in the UK (Beniston 2003; Kovats et al. 2006; Ishigami et al. 2007; Robine et al. 2008; Buwen et al. 2014).

Over the past 100 years an increase in total winter precipitation has been detected over the whole of the UK. Osborn and Maraun (2008) analysed UK precipitation in the period (1961-2006) and detected an overall increase throughout the country with the highest increase in Scotland and north-west England. Assessment of seasonal precipitation change for the same period, detected an increase in spring precipitation over Scotland, the west coast of England and Wales, whereas a decrease has been detected for central, eastern and western England. The total summer precipitation the period (1961-2006), showed a decrease over the UK, except Western Scotland and Northern Ireland and the most western parts of England. Furthermore, the total precipitation rates for autumn showed an increase over the whole of the UK, with the highest increase over east Scotland and southern England (Osborn and Maraun 2008). For the winter season an increase was detected throughout UK with the highest increase over east Scotland and south England (Osborn and Maraun 2008).

Over this time period an increase in extreme precipitation events has been detected in spring, autumn and winter for most regions of the UK, with a reduction in the frequency of such events in summer (Alexander and Jones 2000; Osborn et al. 2000b; Osborn and Maraun 2008). Extreme precipitation events occurred more frequently in western parts of the UK in autumn and early winter (Maraun et al. 2012). An increase in precipitation rates was also more pronounced in UK mountain areas (Hurrell and Van Loon 1997). Seasonal changes in precipitation can be partly related to the shift to the positive NAO index and changes in anti-cyclonic conditions (Alexander and Jones 2000; Osborn and Maraun 2008; Pall et al. 2011). Francis and Vavrus (2012), suggested that Arctic amplification (enhanced Arctic warming relative to the northern hemisphere) may be another reason for prolonged blocking weather patterns in northern mid-latitudes, with subsequent effects on extreme weather events.

Storm events around the British Isles have been increasing over the past 60 years, especially between October and March causing coastal damage and flooding (Lowe et al. 2001; Alexander et al. 2005; Met Office 2014b) This increase in storminess can be correlated with strong westerly winds, due to trends towards a positive NAO index (Rodwell et al. 1999; Hurrell and Deser 2009b). This was confirmed by Jenkins et al. (2009) where it was suggested that more frequent periods of storminess in the UK, (occurred between 1926-1929 and 1990-1999), were related to the positive NAO index. Recent studies showed that an increase in storminess could be also connected with the strengthening of North Atlantic Jet stream which provides a good conditions for formation of active atmospheric depressions (Met Office 2014b).

2.5.1 Climate change in SW England: future projections

The Government agency UKCIP was founded in 1997 by DEFRA, to create and disseminate climate change projections, making climate change impacts more understandable to scientists, policymakers and stakeholders (UKCP09 2011). Climate change models are the most important tool in our understanding of how GHG emissions will affect our climate in the future and what changes we can expect. UKCP09 has improved on the projections of climate change based on UKCP02, with a clearer emphasis on model uncertainty and probability levels, giving the most comprehensive projections on UK climate in 21st century.

The latest UK climate projections were launched in 2009 (UKCP09) and were created using outputs from the regional climate model (RCM) (HadRM3), which used and a baseline period 1961-1990 for a key climate variables (e.g. temperature, precipitation) and allowed more accurate projections at the higher resolution (i.e. 25km). In contrast Global Climate Models (GCMs) such as (HadCM3), give projections on a much lower resolution (e.g. 200-400km) and cannot take into account local factors that impact climate such as mountains (Rummukainen 2010). The RCM that has been used over UK climate projections has been developed by The Hadley Centre of the UK Met Office

(HadRM3) and provided projections for a 'High' (SRES A1FI), 'Medium' (SRES A1B) and 'Low' (SRES B1) scenarios of possible GHG's emissions and different probability levels (10, 50 or 90%) probability that the change will be less than describing values (UKCP09 2012). HadRM3 uses a perturbed physics ensemble which enables the model to use different model variants with different climate parameters to better identify model uncertainties (Murphy et al. 2007; UKCP09 2012). Table 1 presents temperature and precipitation projections for the 2080s in SW England with a high emission scenario (SRES A1FI), and 90% probability level showing the largest increase in summer maximum temperature and winter (UKCP09 2011). The following section will focus on regional scale uncertainties in SW England.

Table 1 Key findings for South West England for the 2080s with a high emission scenario and 90% probability level (UKCP09 2012).

Season	Temperature (T) projections by 2080	Precipitation (P) projections by 2080
Summer	Increase in mean T by 5°C *Uncertainty 1.3-7.9°C* Increase in max T by 6.9°C *Uncertainty 1.3-11.9 °C* Increase in min T by 5.3°C *Uncertainty 1.2-8.8 °C*	Decrease in precipitation by 30% *Uncertainty -58-13%*
Winter	Increase in mean T by 3.4°C *Uncertainty 1.4-5.1°C*	Increase in precipitation by 31% *Uncertainty 5-73%*
Annual	Increase in mean T by 4.5°C to 6.0 °C[1]	Increase in precipitation by 1% *Uncertainty -7-10%*

[1] Increase in annual temperature for SW England was derived from SW England maps

2.5.2 Uncertainties in climate projections for West Cornwall

The main uncertainties for climate change projections arise from modelling uncertainty (incomplete understanding of climate system) GHGs emission uncertainty (amount of the future GHGs emissions), natural climate variability and the fact that all of these three causes of uncertainty occur on different timescales (Murphy et al. 2004). Understanding and quantifying such uncertainties are among the key issue in current discussions on climate change research, and they need to be taken into consideration when making decisions for climate change mitigation and adaptation (Hawkins and

Sutton 2009). RCMs have improved since the first IPCC report in 1990, however they still inherit uncertainty from GCMs (e.g. GHGs emissions, positive feedbacks, natural variability) and regional and local biases in a form of input variables such as topography, coastline or convective precipitation and regional circulation patterns (Stainforth et al. 2005; Hawkins and Sutton 2009; IPCC WG1 5AR 2013b). Local scale uncertainties for West Cornwall are arising from the inability to predict future changes in the NAO index, wind direction and 'warm sea-cold land' interactions and changes in sea surface temperatures (Phillips and McGregor 2001; Hurrell and Deser 2009b; Jenkins et al. 2009). Further analysis of model performance as well as better computing strategies will not just minimise uncertainties but also lead to more accurate decadal projections and therefore better interpretation for future conservation and adaptation strategies (Stainforth et al. 2007; IPCC WG1 5AR 2013c; Hawkins et al. 2014).

2.5.3 National scale climate change impacts on biodiversity (UK)

The 2007 DEFRA report (Hopkins et al. 2007) showed that climate change effects on UK biodiversity have been visible through changes in phenology, species geographic distribution, community composition and invasive species intrusions (Fitter and Fitter 2002; Braithwaite et al. 2006; Mitchell et al. 2007) however there is still a lack of studies at the regional and local scales which are important in order to detect vulnerable plant species and set in place adequate conservation strategies.

Several studies detected changes in the phenology of plant species across the UK. For example Fitter et al.(1995) analysed changes in flowering date in Central England (between 1954 and 1989) and detected earlier flowering by an average of 4 days per 1°C increase. Another study by Sparks et al. (2000) analysed changes in flowering date of 24 plant species in the UK, (between 1875 and 1947) and detected that changes in flowering advanced by 2–10 days per 1°C increase. Furthermore, these phenological changes were significantly related to the changes in CET throughout the same observational period (Sparks et al. 2000). Another example is a study conducted on the island of Guernsey, which analysed changes in the flowering date and duration of 232 species over 27 years (between 1985 and 2011) and detected earlier flowering on average by 5.2 days per decade, whereas flowering duration was reduced on average by 10 days per decade (Bock et al. 2014).

A study by Hickling et al. (2006) showed changes in geographical distribution of species across UK, towards higher latitudes and higher elevations. Hickling et al. (2006) studied 16 taxonomical groups of terrestrial and freshwater environments and out of 329 species a northward shift was detected in 275 species, a southward shift in 52 species, where 2 species remained unchanged. Changes in elevation were detected and 227 species shifted to higher elevation, where 102 species shifted to lower elevation (Hickling et al. 2006).

Analysing change in species range on a national scale showed that species with the ability to use multiple habitats outcompete species with more specialised habitat requirements (Powney et al. 2014). Species which are able to use multiple habitats are less vulnerable to environmental change. Furthermore, Powney et al. (2014) found that taller species were outcompeting smaller species, and species with higher Ellenberg values for nitrogen (N) were outcompeting species with lower N values. These results are evidence for a response to increases in agricultural activity. A decrease in species with lower nitrogen values was especially predominant in southern Britain and it was suggested to be due to widely used fertilizers in agriculture practice. A decline was detected for the species with low moisture (M) Ellenberg values which can be linked with a fact that agricultural use leads to drying of soil systems (Powney et al. 2014), but this may further be linked to changes in precipitation. Powney, et al. (2014) suggested an increase in species that required lower temperatures in the north of Britain can be related to climate change, but negative correlation with species change and temperature in the south Britain could be related to agricultural intensification.

Furthermore in *Change in the British Flora 1987-2004* (Braithwaite et al. 2006) tracked changes in the geographic distribution of plant species at the national scale, showing change (an increase or decrease) for individual species, species groups and broad habitats. Dockerty, Lovett et al, (2003) modelled the impact of climate change on 86 plant lists in 66 nature reserves over UK in the next 100 years. They showed plant species will change their geographical distribution and detected the loss of southern and low altitude habitats in species less resilient to temperature change (Dockerty et al. 2003). To understand current and past-century changes in the geographical distributions of plant species on a local scale and its correlation to local climate variability, more research is needed where historical data are available. Better knowledge of the individual plant response to climate change at the regional and local scale will improve scientific understanding of the drivers of change and will inform improved conservation strategies.

2.5.4 Policy makers - climate change key risks

The post-industrial climate change impact on society and ecosystems has been well understood and it is also known that this impact differs at the national, regional or local scale (McCarty 2001; Milly et al. 2002; Karl and Trenberth 2003; Chen et al. 2006; Church and White 2006; McMichael et al. 2006; Parmesan 2006; Loarie et al. 2009). Suitability for species to persist at the current 'place' will change and in order to make good conservation strategies organisations are operating on different spatial scales in order to identify the magnitude of climate change risk that is placed on biodiversity (Parmesan et al. 2011; Lawson et al. 2012). In order to protect ecosystems, organisations from the global to the local scale were set to identify and conserve threatened, vulnerable and endemic species and habitats. Global scale monitoring gives an understanding of what is happening at the entire species range in order to avoid global extinctions, where regional and local scale monitoring helps in preserving regional biodiversity by keeping ecosystem services and maintaining regional identity (Bassett et al. 2007; IUCN 2008; Rivers et al. 2014; SCBD 2014). Hence, environmental organisations, such as the International Union for Conservation of Nature (IUCN) or World Wide Fund for Nature (WWF), operate on a global scale, whereas Habitats Directive or Natura 2000 Ecological Network (an EU wide network of nature protection areas established under the Habitats Directive in 1992), operate at the European Union scale (NATURA 2000; Arts B. A. S. 2004; IUCN 2008).

National landscape plays an important role in the UK national, regional and local identity, and identifying countryside characters helps to maintain them and avoid uniform landscapes (Bassett et al. 2007; Bowen 2010; Natural England 2012; Paasi 2012). In addition, the 'natural' landscape has been recognised as the most favourable aspect of Cornwall and a questionnaire undertaken in 2008 showed that the main attraction for visitors to the area is its preserved landscape and therefore it is an important part of cultural ecosystem services (MEA 2005; Cornwall Council 2011; Balvanera et al. 2013). Furthermore, 25% of Cornwall belongs to an Area of Outstanding National Beauty, protected areas with status equal to the National Parks, and Cornish landscape has been identified as the most important key element for the regional economy (Cornwall Council 2011).

In order to protect and conserve the Cornish landscape there is the need for more collaborative work and better understanding of local scale climate change impacts on biodiversity so that biodiversity can be managed, maintained, and in some places enhanced in the coming years, whilst maintaining provision of ecosystem services (MEA 2005; Rands et al. 2010). Hence, one of the roles of policy making is to identify key risks and minimise the severity of climate change impacts on society, the natural environment and the economy, through implementation of appropriate planning strategies (Peterson et al. 2003; Füssel 2007). A major challenge for policy makers comes from the range of uncertainties involved with climate change projections (Schneider 2001; Stainforth et al. 2007; IPCC WG1 5AR 2013b), and uncertainty of how biodiversity will change at the local scale and to what extent the likely biological responses will impact the ecosystem services provisioning (Farber et al. 2002; Carpenter et al. 2009; Balvanera et al. 2013; de Oliveira and Berkes 2014; Martinez-Harms et al. 2015). The following section will discuss the role of agencies that are currently in charge (from national to local scales) in developing better policies to adapt and conserve biodiversity and minimise extinction rates in the future.

Risk can be defined as: “The potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is often represented as probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur” (IPCC WG2 5AR 2014). The risk of climate change can be identified through changes in temperature, precipitation and extreme events, and with additional impacts society and on ecosystems, affecting the provision of ecosystem services and therefore human health and geopolitical stability (Nicholson 2001; Breshears et al. 2005; IPCC WG2 4AR 2007). At the national level the UK was the first European country to implement management that acted upon the Biodiversity Action Plan (BAP), published in 1994 to provide plans for protection and conservation of threatened biodiversity.

Management of ecosystems for meeting BAP and NATURA 2000 is conducted in the UK with help from, and regulated by organisations such as the Department for the Environment, Food and Rural Affairs (DEFRA), Natural England, the Environment Agency and the Cornwall Wildlife Trust (CWT), (NATURA 2000), (Table 2). Another EU initiative of Biodiversity 2020 has a goal to stop England's biodiversity loss by 2020, and to put in place measures so that biodiversity is maintained (e.g. by keeping habitats in favourable or recovering conditions and reduce their fragmentation (Defra 2011). These agencies work from national to local scales, and their mutual role is to prevent biodiversity loss by developing conservation strategies and to help regional ecosystems to adapt to climate change and also to direct agriculture, forestry and rural policy to benefit biodiversity.

In Cornwall for example the BAP Volume 4 project started in 2009 as a part of the Cornwall Biodiversity Action Plan with the aim to update the UK BAP list of priority habitats and species (JNCC 2010; BRAS 2011). This project has been split into three sub-projects: geographical areas (with "The Wild Penwith" as one of them), species project and information gathering (CWT 2009b). The main target of the geographic area 'Wild Penwith' was to maintain healthy heathland and wetland habitats and secure their long term management (CWT 2010). This was supported with the help of Natural England and The Farming and Wildlife Advisory Group (FWAG) as they advocated agri-environment schemes. The aim of 'information gathering' (BAP Volume 4 project) was: to establish and map priority habitats, their connectivity, and identify 'key' endangered species. This approach would spatially assess the areas of highest risks and direct the need for conservation strategies. Natural Character Areas project (NCAs-Natural England project) was developed to helped communities to understand the value of the Cornish landscape in order to participate in decisions on policy making (Griffiths et al. 2004; Natural England 2012). The goal of the NCAs was to identify key characteristics of the areas, changes in the landscape through history and important ecosystem services in order to make better guidelines of how to manage and restore such landscapes (Natural England 2012). Three of the classified National Character Areas are part of West Cornwall (Carnmenellis, West Penwith and Lizard) (Natural England 2012). The Landscape Character Study of Cornwall and Isles of Scilly, expanded National Character Areas to the local level and identified 40 diverse Landscape Character Areas within Cornwall which are all contributing to the regional identity of Cornwall (Cornwall Council 2007; Natural England 2012). Understanding the changes in a landscape is only possible with novel research from local to regional level and more understanding of the complex and complicated interactions between climate and biodiversity. Furthermore, more collaboration between broader scale directives (i.e. European Union and agencies at the regional and local scale) is needed, as this will generate more accurate feedback about conservation needs throughout species ranges. This PhD research will not investigate conservation strategies for West Cornwall, however in Chapter 6, it will be discussed why it is important to preserve biodiversity at the regional and local scale.

Table 2 Agencies with an environmental protection role in climate change mitigation and management

	UK Environment Agency	**Natural England**	**Cornwall Wildlife Trust**
Role	To regulate EU legislations	Conservation and sustainable development	Conservation of wildlife and wild places
Priority	Flood risk management and environmental advising	Advisor on natural environment	Manage natural reserve and advise on conservation
Cornwall	BRANCH	West Penwith ESA	Wild Penwith

2.6 Summary

From the second half of the 20th century, a global temperature increase has been detected and it has been associated with an increase in GHGs. However, this increase is not uniform and differs, regionally and locally. Therefore, in order to understand the magnitude of temperature change and its direction on such small scales there is a need for more research. Precipitation change is even more spatially and temporarily variable as it is more dependent on topography and atmospheric circulation. The scientific community recognised the need for regional and local climate variability research, however, such studies have been restricted due to a lack of digitised instrumental records. The first aim of this study is to investigate the local climate variability of West Cornwall using archive (non-digitised) and contemporary weather records. The atmospheric circulation that has the dominant impact on climate of the Northern Europe and United Kingdom is the NAO index and one of the objectives of this PhD research will be to investigate relationships between local climate variability of West Cornwall and the NAO index. The occurrence and impact of extreme events due to climate change has been a fundamental issue of the research in the past decades and this research will investigate whether there has been a change in extreme precipitation events over West Cornwall. This type of research has not been extensive at the regional or local scale over South West England which highlights the importance of this PhD project.

The second part of this literature review showed that climate change had an impact on biodiversity showing changes in phenology, invasive species intrusions, poleward and northward shifts in geographic distributions and species extinction. There has been extensive research on biodiversity change at the global, continental and national scales, however, with a lack of studies on national regional and local scale. Such research is dependent on the availability of historical data, in the case of this PhD research; collection of herbarium records, and contemporary vegetation records. This PhD research will use a novel approach in tracking the changes in geographic distribution changes of plant species, using local historical vegetation records (herbarium collections) for West Cornwall. Globally it has been recognised that biodiversity change has been linked to 20th and 21st centuries climate change, however there is still a missing link for this attribution regionally and locally. This study will investigate, as a part of the third objective, whether Ellenberg values could be used as an environmental change indicator and therefore a link to local climate variability. Local scale studies on climate variability and vegetation change are important as they give better understanding of the change at the local scale, and therefore a good base for policy makers and better conservation strategies.

The following chapters are: Methodology (Chapter 3); results in the form of three papers on; climate variability over West Cornwall (Chapter 4), changes of geographic distribution of vegetation pre and post 1900 (Chapter 5) and the loss of vegetation at the local scale and importance of its conservation (Chapter 6). Final chapter (Chapter 7) is overall discussion and conclusion.

3. Methodology

This Chapter has been divided in two parts; sections 3.1, 3.2, 3.3 and 3.4, address the climate and geographical characteristics of the study region (West Cornwall) whereas the second part (section 3.5) outlines the broad scope of the methodology for the thesis. Further methodological descriptions, as they apply to each chapter are then explained in more detail within each of the empirical Chapters (4, 5 and 6).

3.1 Study site

Cornwall is a county located in South West (SW) England covering an area of 3,653 km^2. It is a peninsula and its climate is dominated by a strong maritime effect (Met Office 2011) the specific climatic conditions of this region will be discussed in more detail in section 3.2. The study site for this project is West Cornwall, the most westerly part of the county (Fig. 5). West Cornwall was chosen as a study site for several reasons: it represents a key area for climatic research being largely free of urban heat island effects (Fig. 10), and with good availability of local and long term instrumental data and. Given the impact of North Atlantic influences on the British climate, and impact of westerly winds on West Cornwall, this study site is well placed to ask questions concerning the importance of the NAO on rainfall and temperature trends. Furthermore, analysing local climate variability is a good base to understand its impact on vegetation at the fine scale (Met Office 2011). Good collection of historical vegetation records which allows analysing the changes in geographical distribution of plant species in past 200 years as ‘Cornish landscape’ represents an important part of regional identity and economy (Cornwall Council 2007; Natural England 2012; Paasi 2012).

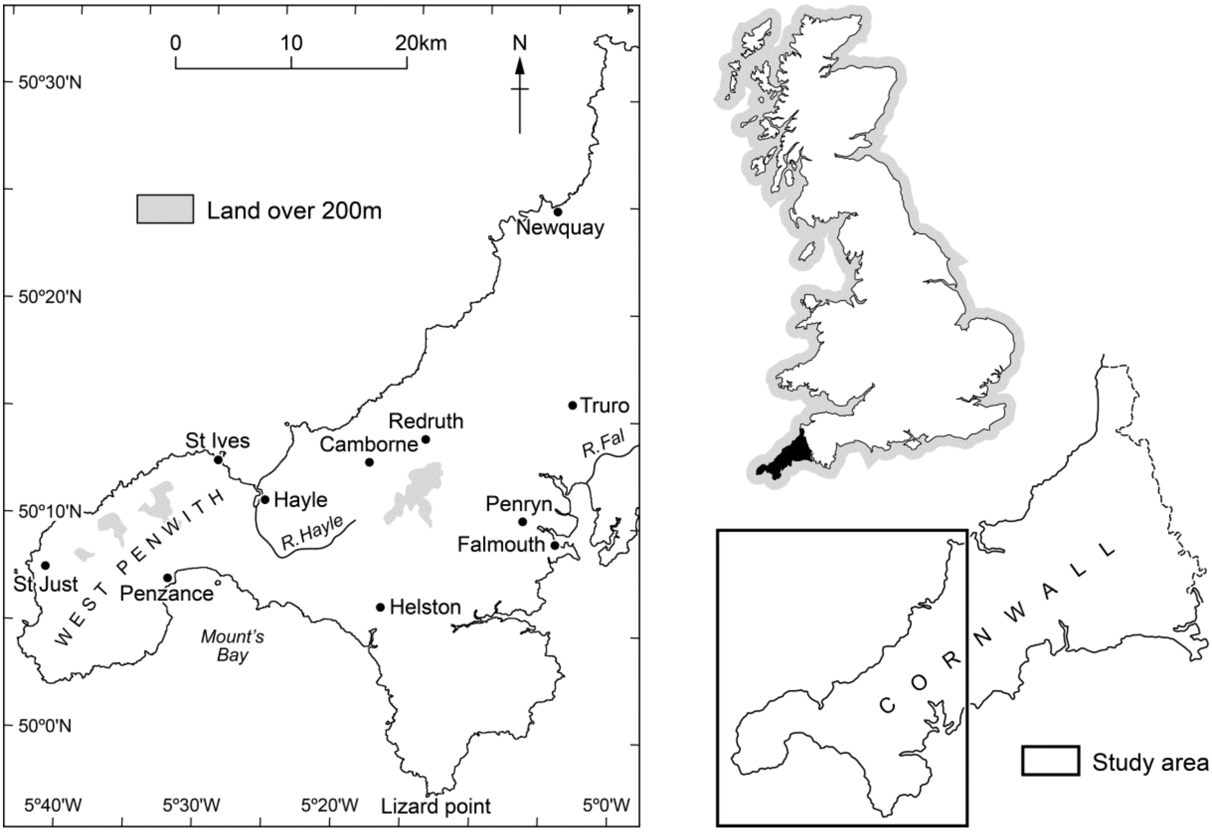


Figure 5 Study site - West Cornwall

3.2 Climate of South West England (SW) - Cornwall

Cornwall, in South West England, forms part of a peninsula which is the most south-westerly part of the UK, a region where maritime effects play an important climatic role (Met Office 2011). The following paragraph will summarise the current climate of Cornwall.

There are several factors that have an impact on the regional temperature; latitude, oceans, and altitude. Lower latitudes receive more sun insolation as a result of the higher angle of sun radiation relative to the angle of the Earth axis. The Atlantic Ocean affects the climate of the South West in two main ways: ocean heat capacity (i.e. land cools faster than the ocean) and North Atlantic Drift an extension of the Gulf Stream. Furthermore, altitude is an important factor in temperature change decrease (i.e. an a decrease by 0.65°C per 100 m) due to less sun radiation reflected back to the atmosphere, slope gradient and, and the fact that the air pressure decreases with an increase in altitude, leading to lower kinetic energy between air molecules and therefore lower temperatures. Maritime effect prevents very low temperatures over SW England and annual average temperature was calculated to be 10-12°C for the period between

1971-2001 whereas, due to an increase in altitude, temperatures are lower over the moors of Bodmin, Dartmoor and Exmoor with an annual average temperature of 8°C (Met Office 2011). Spatial distribution of temperatures can also be affected by changes in frontal systems and the wind (Met Office 2015b).

The precipitation over SW England is affected by westerlies which absorb a large quantity of water vapour over the Atlantic Ocean, bringing higher precipitation rates to western parts of United Kingdom. Furthermore, SW England is prone to some of the strongest winds in the British Isles (beside western Scotland) and this has an impact on the spatial distribution of precipitation (Met Office 2011; Phillips and McGregor 2001). Coastal areas of SW England receive annual total precipitation between 900-1000 mm per year (Met Office 2011). Precipitation increases with a change in altitude, due to an orographic effect, over Dartmoor, Exmoor and Bodmin Moor (i.e. 2000 mm per year) (Met Office 2011). A previous study that analysed precipitation totals in Cornwall for the period 1957-96, showed the largest precipitation increase in early winter (November to January), for St. Mawgan and Culdrose, when the strength of the westerly winds is at their peak (Hurrell and Van Loon 1997; Phillips and McGregor 2001). This supports an argument that the high precipitation during winter months could be linked with the annual and inter-annual variability of the NAO index (Hurell 1995; Hurrell and Van Loon 1997; Hurrell and Deser 2009a). Land-sea interactions play an important role in driving the spatial distribution of precipitation, and this is seen in higher precipitation over coastal areas than inland areas during the winter seasons (Phillips and McGregor 2001).The precipitation over SW England (Cornwall) is also determined by sea temperatures and the driest period was detected in spring and summer (April to July) when the sea is relatively cold, which is followed by an increase in precipitation during the autumn and beginning of the winter when the sea is still relatively warm (Met Office 2011). Another factor impacting the weather in Cornwall is the interaction of different air masses (e.g. Artic Maritime, Polar Maritime, Tropical Maritime, Tropical Continental and Polar Continental) over UK. For example, when a Tropical Continental air mass (warm and wet) is stronger it creates a warm front which can produce long periods of lighter precipitation. The opposite happens when a cold air mass is stronger and it creates a cold front with heavy, dense precipitation. Both fronts can create a veering wind; a clockwise change in wind direction with a change in altitude (Met Office 2015b). Figure 6 shows a synoptic map for where a warm front passing over the

United Kingdom is weakening with a decrease in pressure, and another warm front is approaching. Beside precipitation, warm fronts can bring colder temperatures before its actual arrival, and a steady rise in temperatures while it is passing, and after it has passed (Met Office 2015a). It was detected that SW England had the lowest amount of snow in the UK in the period 1971-2001, mostly occurring on upland areas, where lying snow was remaining for up to 20 days (Exmoor, Dartmoor) (Met Office 2011).

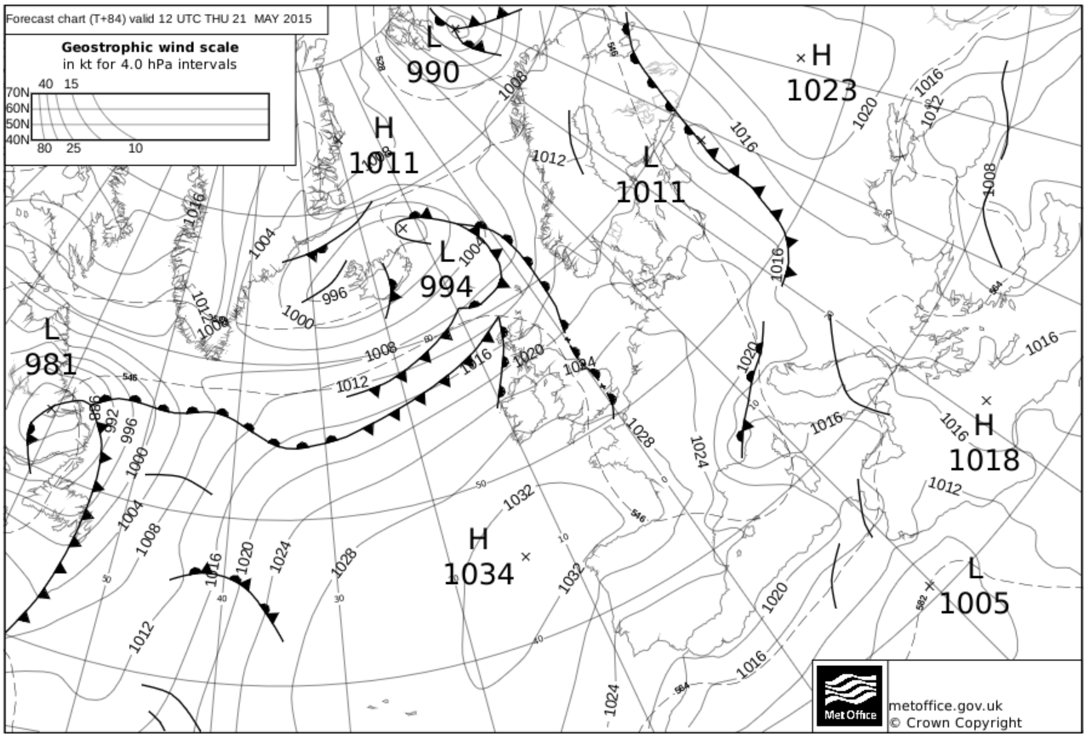


Figure 6 Synoptic map for UK on 21/05/2015 (Met Office 2015a)

3.3 Topography, geology and soil

Cornwall is part of the south west peninsula of the United Kingdom and it is situated west of the river Tamar with 697 km of coastline. The north coast of Cornwall is dominated by steep cliffs whereas the topography of the south coast has more gentle topography. The south coast is characterised by steep river valleys such as Lamorna Valley and Penberth Valley and with an estuary of the river Fal. Inland Cornwall is a plateau formed by granite intrusion, and it is a topographically higher zone. The altitude of the granite moors of St. Austell, Carnmenellis and Land's End varies between 240-300 m.a.s.l. where further to NE is Bodmin Moor with the highest point of Cornwall

(Brown Willy 420 m.a.s.l.) (Selwood et al. 1999) (Fig. 7). Different topography and different slope gradients over Cornwall are important for soil distribution and geological composition determinates topography.

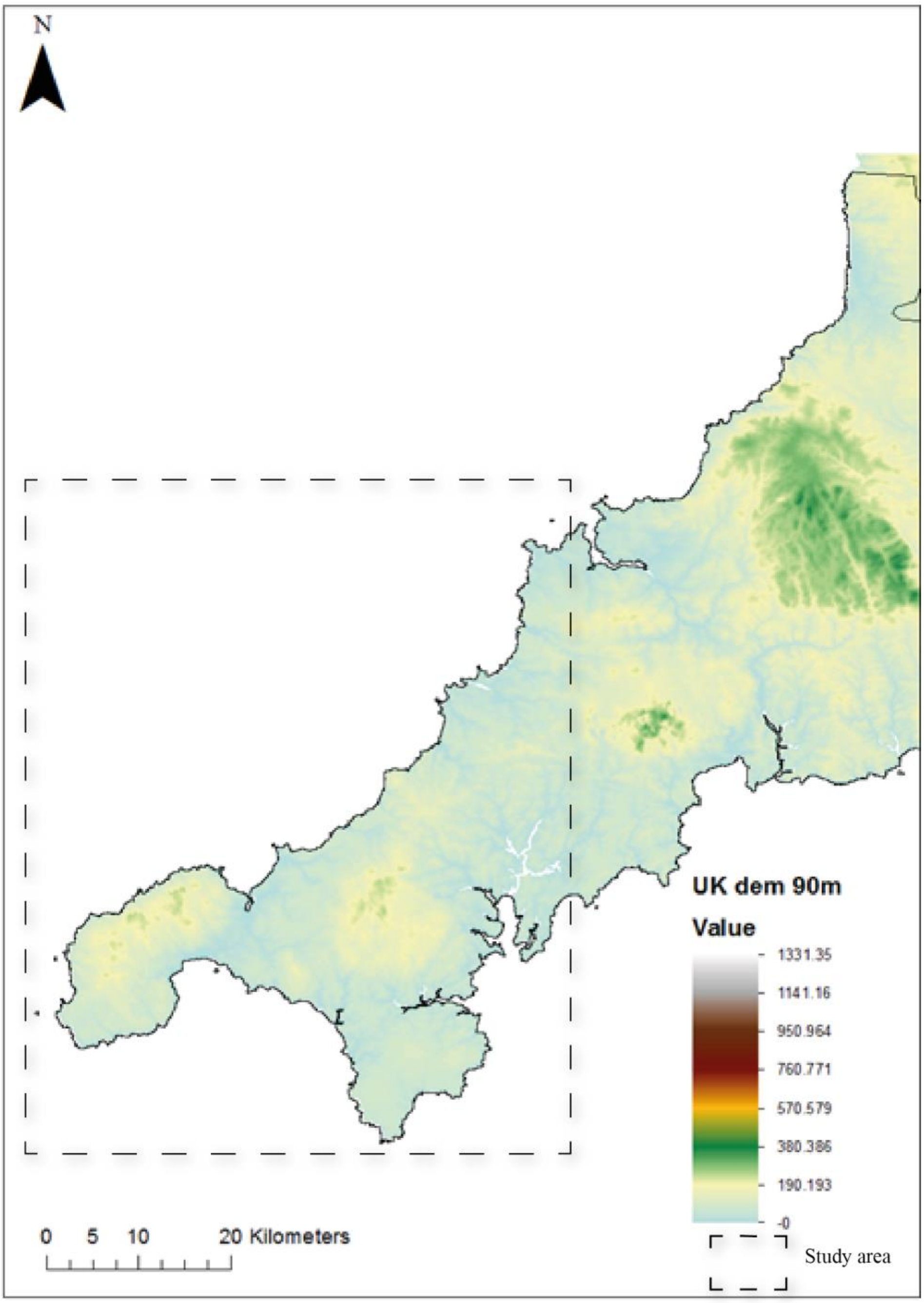


Figure 7 Digital Elevation Model UK (DEM), 90m – Cornwall (Digimap 2009)

Geologically, Cornwall is known as eroded Cornubian massif, which was formed during the Variscan orogeny (late Carbobniferous-Devonian) due to the northward convergence and collision of Gondwana and Laurasia (LeBoutillier 2002; Brenchley and Rawson 2006). During the early Permian (~ 300-280 Ma), granite intrusion formed the uplifted areas of Cornwall such as Land’s End, Carnmenellis, St Austell and Bodmin Moor (Fig. 8). These granite intrusions were part of the wider, Cornubian batholith formation, which runs from the Isles of Scilly in the west, to Dartmoor in the east (Charoy 1986; Brenchley and Rawson 2006). Separate satellite granite intrusions are visible at St Michael’s Mount, Tregonning-Godolphin, Carn Brea, Carnmarth, St. Agnes Beacon, Cligga Head, Castle-an-Dinas, Belowda Beacon, Kit Hill and Hingston Down (LeBoutillier 2002). Granite gravel and sand is formed among these intrusions which caused the formation of acidic soils pH<6.5. These Granite based acidic soils are rich in minerals such as Arsenic (As), Copper (Cu), Lead (Pb), Tin (Sn), Tungsten (W) and low in Iron (Fe), Cerium (Ce), Chromium (Cr) and Nickel (Ni) (Fig. 9). Granite intrusions are surrounded by sedimentary basins; the Gramscatho Basin and the Trevone basin which were formed during Middle and Late Middle Devonian (LeBoutillier 2002; Leveridge and Shail 2011), and these sedimentary basins are bounded by NW- SE faults. Furthermore, the basins were filed with sandstones, mudstones, mud deposits and subordinate conglomerate and with volcanic sequences between these sediments.

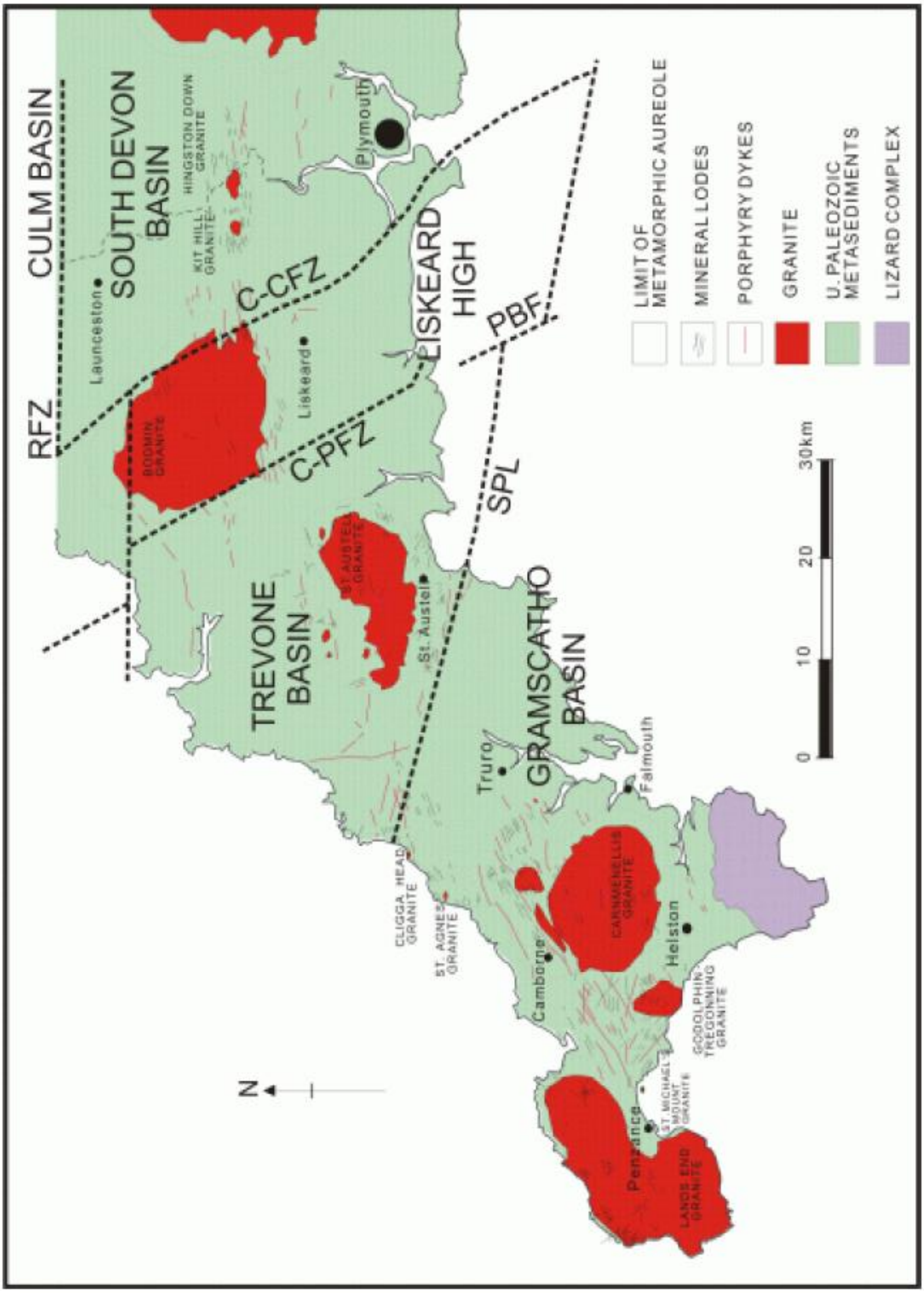
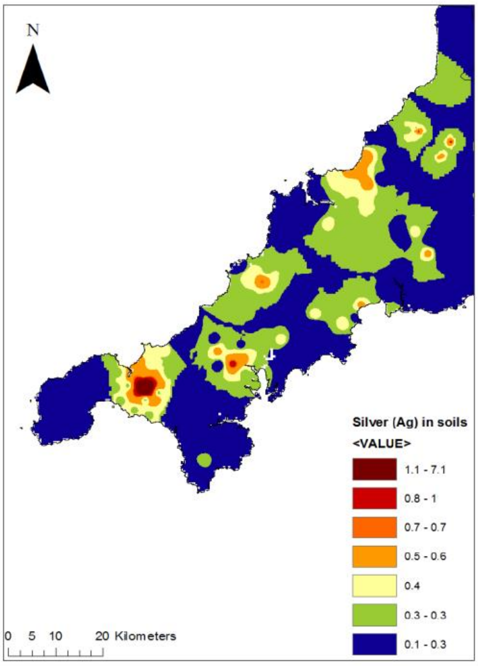
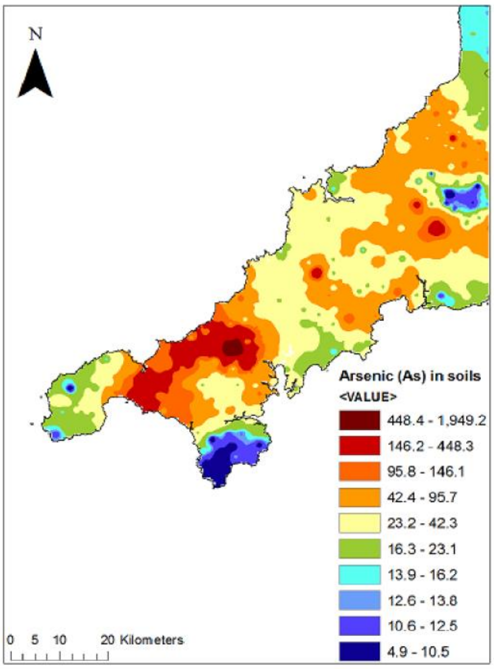


Figure 8 Simplified geological map of Cornwall showing granite intrusions, sedimentary basins, C-PFZ, Cardinham-Portnadler Fault Zone; C-CFZ, Cambeak-Cawsand Fault Zone: SPL, Start-Perranporth Line; PBF, Plymouth Bay Fault; RFZ, Rinsey Fault Zone (LeBoutillier 2002)

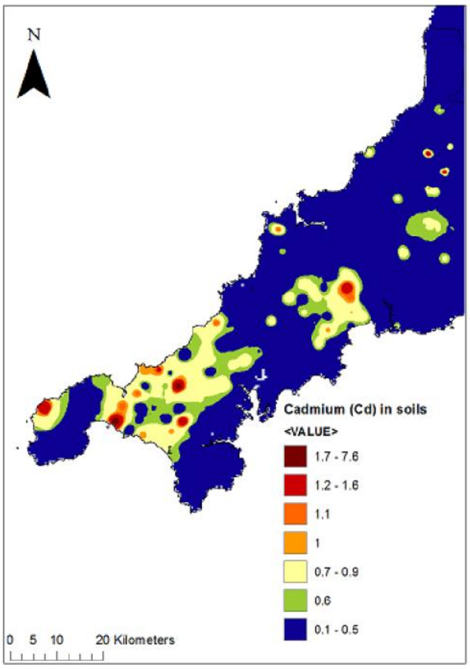
Sedimentary rocks are responsible for the creation of alkaline soils, such as clay with pH>8.5. Such soils are rich in Iron (Fe), Cerium (Ce), Chromium (Cr) and lower in Cadmium (Cd). The Lizard Complex is a part of the oceanic crust and has been divided into three parts; Lizard Head, Goonhilly Downs and Crousa Downs. The Lizard Head is the oldest geological structure in South West Cornwall dating to Lower Ordovician. The rock types on Lizard are serpentinite, gabbro, schist and gneiss. Soils developed on such rocks are very nutrient poor with low levels of Cadmium (Cd), Arsenic (As), Potassium (K), Uranium (U) and Antimony (Sb) (Fig. 9). The geological structure of Cornwall led to the emergence of the mining industry and allowed mineral extraction, particularly in metals (Sn and Cu), china clay and china stone and building materials (Selwood et al. 1999). Minerals important for the mining industry such as Antimony (Sb), Arsenic (As), Cadmium (Cd), Copper (Cu), Lead (Pb), Zink (Zn), can contribute to phytotoxic effects on plants which are visible in changes in growth and metabolism it has been suggested that some plant species are more resilient to these minerals than others, however there is a lack of research on these impacts on individual plant species (Bech et al. 1997; Nakamaru and Sekine 2008; Nagajyoti et al. 2010).


N
Silver (Ag) in soils
<VALUE>
1.1 - 7.1
0.8 - 1
0.7 - 0.7
0.5 - 0.6
0.4
0.3 - 0.3
0.1 - 0.3
0 5 10 20 Kilometers

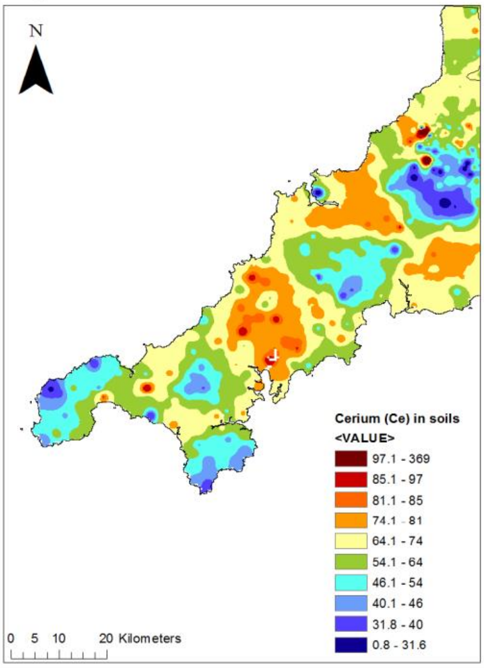
a)


N
Arsenic (As) in soils
<VALUE>
448.4 - 1,949.2
146.2 - 448.3
95.8 - 146.1
42.4 - 95.7
23.2 - 42.3
16.3 - 23.1
13.9 - 16.2
12.6 - 13.8
10.6 - 12.5
4.9 - 10.5
0 5 10 20 Kilometers

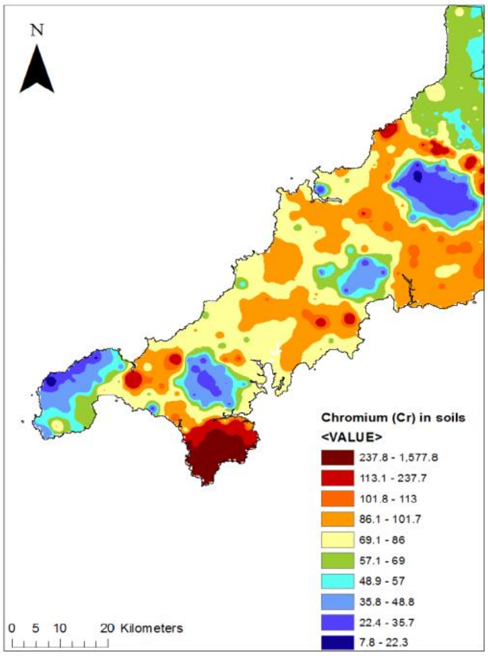
b)


N
Cadmium (Cd) in soils
<VALUE>
1.7 - 7.6
1.2 - 1.6
1.1
1
0.7 - 0.9
0.6
0.1 - 0.5
0 5 10 20 Kilometers

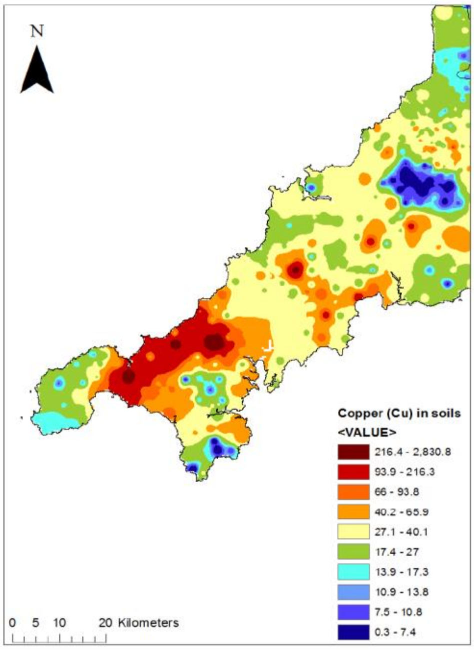
c)


N
Cerium (Ce) in soils
<VALUE>
97.1 - 369
85.1 - 97
81.1 - 85
74.1 - 81
64.1 - 74
54.1 - 64
46.1 - 54
40.1 - 46
31.8 - 40
0.8 - 31.6
0 5 10 20 Kilometers

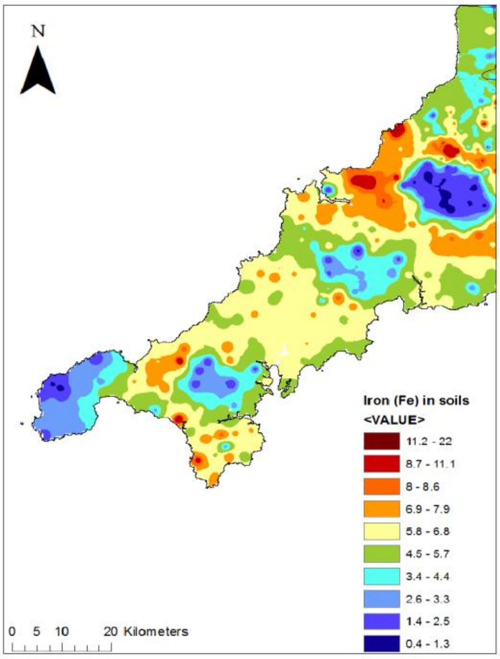
d)


N
Chromium (Cr) in soils
<VALUE>
237.8 - 1,577.8
113.1 - 237.7
101.8 - 113
86.1 - 101.7
69.1 - 86
57.1 - 69
48.9 - 57
35.8 - 48.8
22.4 - 35.7
7.8 - 22.3
0 5 10 20 Kilometers

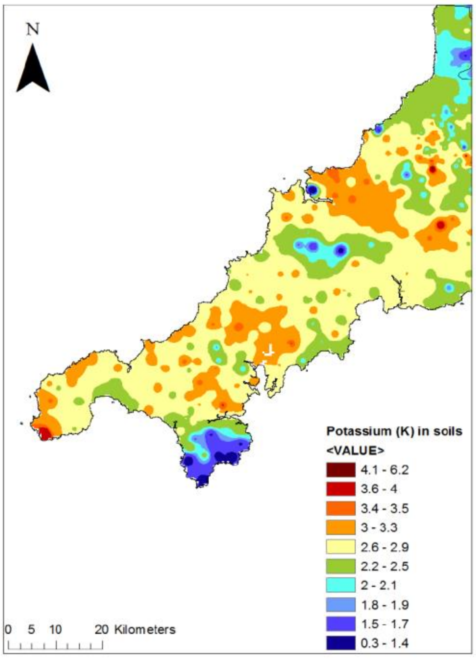
e)


N
Copper (Cu) in soils
<VALUE>
216.4 - 2,830.8
93.9 - 216.3
66 - 93.8
40.2 - 65.9
27.1 - 40.1
17.4 - 27
13.9 - 17.3
10.9 - 13.8
7.5 - 10.8
0.3 - 7.4
0 5 10 20 Kilometers

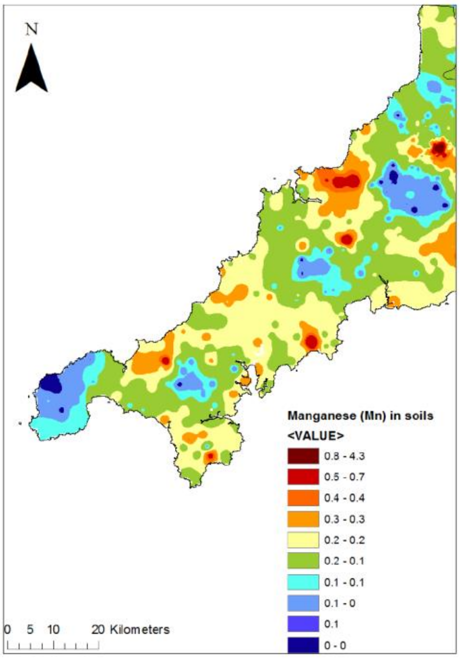
f)


N
Iron (Fe) in soils
<VALUE>
11.2 - 22
8.7 - 11.1
8 - 8.6
6.9 - 7.9
5.8 - 6.8
4.5 - 5.7
3.4 - 4.4
2.6 - 3.3
1.4 - 2.5
0.4 - 1.3
0 5 10 20 Kilometers

g)


N
Potassium (K) in soils
<VALUE>
4.1 - 6.2
3.6 - 4
3.4 - 3.5
3 - 3.3
2.6 - 2.9
2.2 - 2.5
2 - 2.1
1.8 - 1.9
1.5 - 1.7
0.3 - 1.4
0 5 10 20 Kilometers

h)


N
Manganese (Mn) in soils
<VALUE>
0.8 - 4.3
0.5 - 0.7
0.4 - 0.4
0.3 - 0.3
0.2 - 0.2
0.2 - 0.1
0.1 - 0.1
0.1 - 0
0.1
0 - 0
0 5 10 20 Kilometers

i)

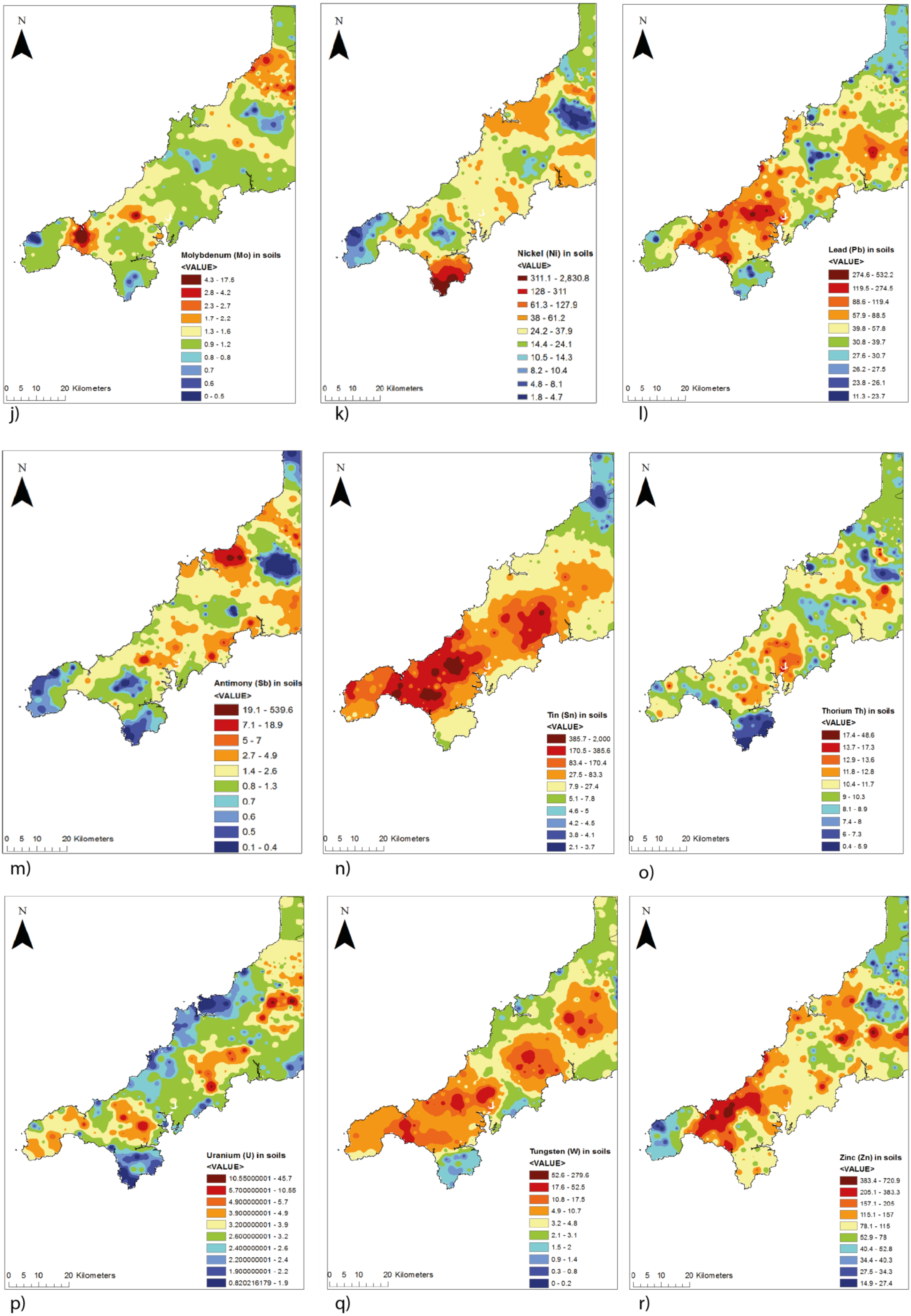


Figure 9 Minerals in soil-Cornwall (BGS 2015)

3.4 Land use change

As previously discussed in section 2.3, land use change also has an important impact on spatial and temporal changes in biodiversity. Cornwall was inhabited for the last ten thousand years and the primary land cover until Neolithic and Bronze Ages (6000-2500 BP), was forest, which was cut down when hunting communities were exchanged for farming communities (CWT 2014). The biggest change to the Cornish landscape occurred with deforestation and the establishment of agriculture, resulting in heathland development (Howard 1997). Agriculture was a primary economic activity until the 13th century, when it was replaced by the mining industry. However, the last mines were closed in the 20th century and the ruins of the mining industry became an important part of Cornwall's heritage and regional identity (Natural England 2012). Now some of the old mines are used for tourism, and traditional agriculture has been restored as the landscape has become a major driver of the Cornish economy (Cornwall Council 2011). Therefore, agencies such as DEFRA or CWT work on the regional scale to minimise the threats of land use change on biodiversity. As it was previously discussed in a section 2.7; such agencies, encourage traditional agriculture management to prevent intensification of agriculture practice or over grazing and in that way prevent a loss of natural vegetation (Hopkins et al. 2007; CWT 2009a; Defra 2011) (Fig. 10). This has been supported through Environmental Stewardship (ES) and Higher Level Stewardship (HLS), an agri-environment schemes that provide funding to farmers and other land managers (Natural England 2013). As Cornish landscape is an important part of regional economy and Cornwall is part Area of Outstanding Natural Beauty it has been the main goal to protect and conserve 'Cornish landscape' and minimise initial land use changes as much as possible (McCollin et al. 2000; Cornwall Council 2011). Nevertheless, it is important to acknowledge that land use change had an impact on Cornish landscape in post-industrial period, there still lack of regional studies on magnitude, direction and speed of these changes (Ordonez et al. 2014).

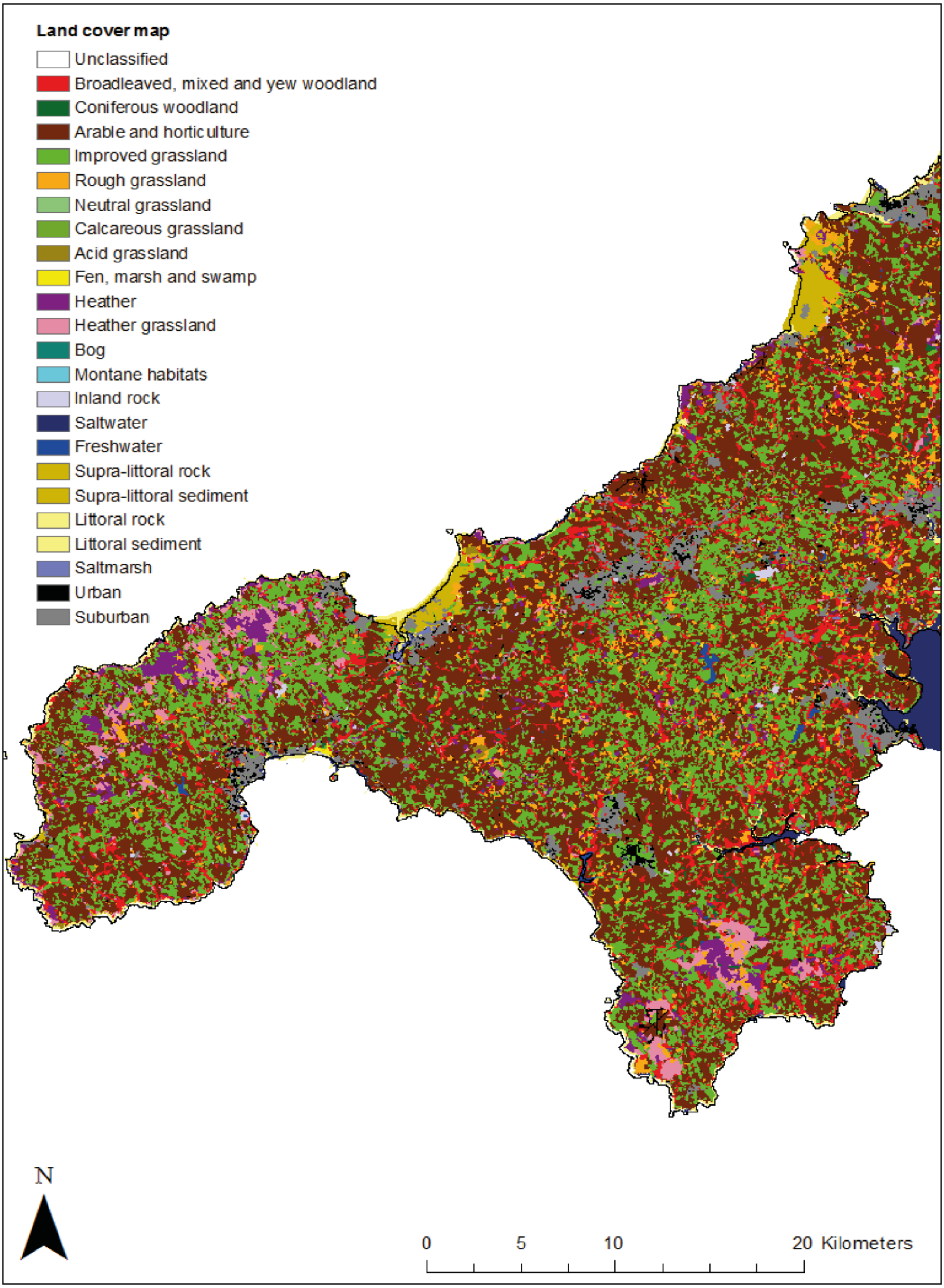


Figure 10 Land cover - West Cornwall (Digimap 2007)

3.5 Methods used in this PhD research

3.5.1 Broad analytical methods used in chapter 4

In the first empirical chapter (Chapter 4) of this PhD researches regional (West Cornwall) instrumental weather data that were analysed. Data covered the time periods of the 19th, 20th and the beginning of the 21st century. The majority of data sets required initial aggregation and digitisation from several archives:

- the UK Meteorological Office
- the Royal Cornwall Polytechnic Society
- Trengwainton Garden and Cornwall County Council Record Office

Data for Camborne, Trengwainton Garden, Falmouth and Helston were obtained from archives and digitised. There are two main uncertainties in historical weather data. The first uncertainty is the quality of the records, therefore data sets were quality checked twice; for missing values, possible outliers (e.g. possible outliers on the plots were double checked with the archive documents to ensure they had not been entered erroneously) and for inconsistency in the maximum and minimum temperature data (e.g. where minimum temperature was larger than maximum). Before addressing the second uncertainty, all data required conversion into modern units (°C and mm) achieved through automation in Microsoft Excel. The second uncertainty in historical weather data could be found in data that are not homogenized (Staudt et al. 2007; Vincent et al. 2012; Dunn et al. 2014). Hence the next step in pre-processing the data was to perform tests for homogeneity of variance. Homogeneity adjustment is a standard procedure in the analysis of historical weather data and it is a necessary step, as changes in instruments, station location, measuring technique, or observational times may occur (Staudt et al. 2007; Brunet and Jones 2011), and these can cause trends in data independent of climate variability. Since we had a lack of nearby stations and therefore an inability to perform relative homogeneity analysis (Alexandersson 1986; Staudt et al. 2007; Firat et al. 2011), we applied absolute homogenization and tested homogeneity of variance within each station, using Levene, and Brown-Forsythe tests (Roth 1983; Caloiero et al. 2011; Martín et al. 2012). Prior to the trend analysis, years with one missing month for temperature records were excluded from the analysis as well as the years with 10 % missing values for daily data. The same rule was used for the seasonal data. Seasons in this study were assigned in the following way: Winter-December, January, February (DJF); Spring-March, April, May (MAM); Summer-June, July, August (JJA), and Autumn-September, October, November (SON). For precipitation records, the rule was to exclude all the years and seasons where data for the whole month were missing. This is because only in these months can it be assumed that there was no precipitation records. For trend detection Mann-Kendall and seasonal Mann-Kendall tests were used. Both are recognised as robust methods for trend detection, as normality of distribution is not a requirement, and missing values are tolerated, which is usually the case with instrumental data (Brunetti et al. 2000b; Burn and Hag Elnur 2002; Yue et al. 2002; Helsel and Frans 2006). The Mann-Kendall test detects monotonic positive or negative trends for annual means, where the seasonal Mann-Kendall test calculates the score for each season (Hess et al. 2001; Kahya and Kalaycı 2004). In order to calculate the magnitude of the trend, Sen’s slope estimator (Q score), a non-parametric version of linear regression was used (i.e. uses the difference between observed data and median value of y) (Olofintoye and Sule 2010; Salmi et al. 2002).

The correlation between instrumental data (annual and seasonal) and the NAO index was analysed by Spearman’s rho non parametric test. As there are two types of NAO indices, the station based and the Principal Component (PC) NAO index, we performed correlation for both. The station based NAO index is calculated from instrumental sea level pressure (SLP) for Lisbon and Stykkisholmur/Reykjavik with the records accessible further back in time, where the PC NAO index was calculated using an Empirical Orthogonal Function (EOF) of SLP anomalies over the Atlantic sector (i.e. 20°–80°N; 90°W–40°E) and presents more accurate movements of SLP anomalies (Lifland 2003; Hurrell and Deser 2009b). Changes in the frequency and magnitude of extreme precipitation events will be examined by return period analysis using the Gringorten formula (Fowler and Kilsby 2003).

3.5.2 Broad analytical methods used in chapter 5

In the second empirical chapter (Chapter 5), changes in geographical distribution of plant species in West Cornwall were analysed. Historical vegetation records were used from “The Flora of Cornwall” (Davey 1909), a collection of all known herbarium data and field observations in the county of Cornwall and the Scilly Isles from the 18th and 19th centuries. Although the collection contains plant specimens recorded in the 18th century, records for the species that were analysed in this study were not found prior to the 19th century. Historical vegetation records contained native and non-native species and in this study they are referred to as pre-1900. As historical data contains textual descriptions of localities where plant specimens were found (e.g. “*Achillea ptarmica*, first record: 1769; district 7: Porkellis Moor, Wendron, Coverack, Emyln”) (Davey 1909) page 247), rather than explicit definitions of longitude and latitude, it was essential to address several uncertainties in the geo-referencing process (taxonomical inaccuracy, synonyms, spatial error, bias associated with the frequency and time spent on data collection (areas or species could be poorly sampled)). The latter uncertainty proved particularly challenging (Graham et al. 2004), as in this study it was not possible to use automated geo-referenced tools, which were developed for the United States, but are not applicable for the UK (Soberon and Peterson 2004; Guralnick et al. 2006).

For this PhD research, contemporary vegetation records from West Cornwall were formed from native and non-native plant species, which were randomly selected from the currently available database of British flora; “New Atlas of British and Irish Flora” (Preston et al. 2002). The selection included the plant species that could be found in West Cornwall in the 19th century. This contemporary vegetation records is referred to in this study as post-1900.

The next step was to search for the selected species in “The Flora of Cornwall” (Davey 1909) in order to create an historical vegetation digital database and to geo-reference the data. This was required in order to be able to conduct spatio-temporal analysis (pre-1900 vs post-1900) of changes in the geographical distribution of plant species in West Cornwall.

Historical vegetation records (pre-1900) that were found in Davey’s collection (1909), were geo-referenced as accurately as possible using Google Earth and cross-checked with online Ordnance Survey maps (1:2500), (OS 2010). Specimens which were found to have very ambiguous locality descriptions (e.g. “West Penwith”- which covers a large area) were excluded from the study. Furthermore, species without published Ellenberg values or with incorrect taxonomy or synonyms were also excluded from the database and the analysis, which was consistently followed. Historical vegetation records (pre-1900) were imported into ArcGIS and the first step was to address the spatial uncertainty and determine its extent, so that it could be applied to each geo-referenced record of historical vegetation dataset (Rocchini et al. 2011; Lavoie 2013). Spatial uncertainty was calculated using a point radius method, developed for historical data without geographic coordinates (Wieczorek et al. 2004). To arrive at a suitable radius size to best represent this uncertainty, a maximum distance (from the centre of the species locality to their furthest end) for the localities of 50 random plant species was established using Google Earth. Then the upper quartile of this distance was calculated and found to be 1.5 km. This value was used as an uncertainty radius around the location of each specimen in ArcGIS. Upon creation of 1.5 km uncertainty buffers in ArcGIS, they were attributed to the spatial joints of 10 km grid cells in West Cornwall.

The next step was to import into ArcGIS, the current geographical distribution of plant species in West Cornwall (post-1900). The geospatial reference for contemporary vegetation records was downloaded in 10 km grid cell resolution, which was available from an online database (NBN 2013). To understand the changes in geographical distribution of plant species pre-1900 and post-1900, we performed spatial analysis in ArcGIS using Modelling tools (e.g. Intersect tool) to identify the species overlap and species loss.

To investigate if Ellenberg values could be used as environmental change proxies six indicators were analysed in this study: three Ellenberg values (Light (L), moisture (M) and nitrogen (N)) and three climatic indicators (mean January temperature temperature (Tjan), mean July temperature (Tjul) and mean precipitation of range (RR) are referred to in this PhD research as Environmental indicator values. The latter were derived by Hill et al. (2004) from mean climatic values of the 10 km grid cells for the British Isles. To analyse whether there was a correlation between Ellenberg values/environmental indicator values and changes in geographical distribution (pre-1900 vs post-1900) of plant species three properties were investigated:

- The change in the mean range of overall distributions in 10 km grid cells
- The percentage range contraction (i.e. the area that was occupied pre-1900 but unrecorded in recent records).
- The percentage range expansion (i.e. the area that was not recorded pre-1900, but for which recent records exist)

As Ellenberg indicator values are constructed of groups (i.e. 1-9 or 1-12), Environmental indicator values (Tjan, Tjul and RR) were also divided in 8 equal size groups, with for example, group 1, representing coldest/driest species and group 8, representing warmest/wettest species. To determine whether these changes were significantly different, depending on the value of Ellenberg indicator/environmental indicator values, the Mann-Whitney U test was used with a significance level of 0.05.

3.5.3 Broad analytical methods used in chapter 6

The third empirical chapter (Chapter 6) analysed changes in geographical distribution of plant species at the local scale as well as local extinctions. In order to do this, the study site of West Cornwall was divided into three areas: North Border Cells (NBC), Central West Cornwall Cells (CWCC) and South Border Cells (SBC). Such division was made to show species decline and loss locally, at their south range of United Kingdom, as poleward movement could reduce their national range size (Francisco-Ortega et al. 2000; Lesica and McCune 2004; McKay et al. 2005; Chen et al. 2011; Kueffer et al. 2014), and minimise their adaptation and migration potential (Aguilar et al. 2008; Gaston and Fuller 2009; Imbach et al. 2011; Alsos et al. 2012). To analyse species loss in each of these three areas, attributed tables (past vs. present) for each 10km grid cells within each particular area (i.e. North Border Cells) in ArcGIS, were cross-checked to detect 'species loss' and, therefore, show the loss at the local scale between historical and contemporary records. To understand what is happening with locally lost species from West Cornwall at the national scale, changes in plant species geographic distribution at the local scale (West Cornwall) were matched to the changes in their distribution at the national scale (Braithwaite et al. 2006; Parmesan 2006). To detect any differences in species geographical distribution and their loss locally (i.e. lost species from NBC, CWCC and SBC) vs their change at the national scale data from "*Change in the British Flora 1987-2004*" (Braithwaite et al. 2006) was used. Braithwaite et al.

(2006) analysed the changes in vegetation at the national scale by looking at (1) national range change in the individual species, (2) national range change in the species group and (3) national range change in the broad habitat (Braithwaite et al. 2006). More on this method was described in Braithwaite et al (2006). The loss of plant species from whole area of West Cornwall was investigated by comparing attribute tables in ArcGIS for the pre-1900 and post-1900 vegetation records. It was also tracked which of these species were on the IUCN Red List and BAP (Biodiversity Action Plan-volume 4) list (Natural England 2012; IUCN 2014)

4. Present and historical climate variability in South West England

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Author contributions:

A. Kosanic conceived and designed the experiments, formulated the research hypotheses (with guidance from SH and KA). AK and IK analysed the data. SH, KA, IK and AK co-wrote the paper but the writing was led by AK with iterative comments and input from other authors.

4.1 Abstract

West Cornwall is the most south westerly part of mainland United Kingdom with a strong maritime climate. This paper analyses the earliest archived instrumental meteorological records collected in West Cornwall (SW England). Observations were obtained from the Met Office archive (Camborne 1957–2010; Culdrose 1985–2011), Trengwainton Garden (1940–2010), and from the Royal Cornwall Polytechnic Society, (data for Falmouth (1880–1952) and Helston (1843–1888)). Homogeneity tests were used (Levene and Brown-Forsythe tests) to exclude any trends not related to climate variability. The data exhibit trends in annual mean and maximum temperatures over the timescales analysed, and show a general temperature increase in the 20th and 21st century. Annual and seasonal temperature change was found to vary locally with strongly positive trends in autumn, spring and summer seasons. Trends in precipitation are positive only for the 19th century and only for one station. Correlation with the North Atlantic Oscillation (NAO) index gives negative results for precipitation data. However correlation with the NAO index is positive with temperature, especially in the winter season. Return period analysis shows a decrease in intensity and frequency of extreme precipitation events in the post 1975 period (Camborne and Trengwainton Garden stations). Climate change in the 20th century and future continued warming is likely to have major implications on biodiversity in this region.

4.2 Introduction

Climate change is affecting ecosystems worldwide, and can be seen in the pattern of vegetation change (Woodward and Williams 1987; Gottfried et al. 1999; Parmesan and Yohe 2003; Parmesan et al. 2011). Despite considerable research on global climate change (IPCC WG1 5AR 2013a), its impacts and significance at regional or local scales is relatively less studied, mainly due to limited availability of long term instrumental data (Christidis et al. 2005; Brunet and Jones 2011) and uncertainties in regional climate modelling. Analysis of historical instrumental data requires considerable effort in translating information from museums and archives before quantitative analysis can take place. However, detection of climatic effects at the local and regional scales is urgently needed to enable policy makers to identify key risks and minimise the impacts of climate change on ecosystems and society (Walther et al. 2002; Parmesan and Yohe 2003; Colombo et al. 2007; Brunet and Jones 2011). At present there are no studies assessing the nature of climate change from many western parts of the British Isles, areas where the influence of North Atlantic Oscillation (NAO) changes may be expected to play a significant role in local and regional climate. As a result, we have chosen West Cornwall (at the tip of the most westerly peninsula of the UK) as our study site for several reasons. It represents a prime area for climatic research being largely free of urban heat island effects and with good availability of local and long term instrumental data. In addition, given the impact of North Atlantic influences on the British climate, data from West Cornwall are well placed to ask questions concerning the importance of the NAO on rainfall and temperature trends. Furthermore, this knowledge will help more broadly as a baseline data set in tracking vegetation change in this area over the past century allowing better understanding of climate and climate variability. This latter issue will be examined in a future paper and is not discussed here. The first aim of this paper is to analyse instrumental data from historic weather archives by describing seasonal, decadal or multi decadal trends over West Cornwall. The second aim is to analyse the relationship between weather records and value of the NAO index atmospheric circulation which is known to have a profound effect on North Atlantic and European climate (Hurrell et al. 2003; Hurrell and Deser 2009b). The strong relationship between the positive mode (between mid-1960s to mid-1990s) of the NAO index and Northern European winters has been detected, and is visible through increased storminess, higher precipitation rates and above average surface temperatures

(Hurrell and Van Loon 1997; Hurrell and Deser 2009b). The negative mode of the NAO index (which has prevailed in the past 15 years) is recognised to bring lower than average winter surface temperatures and reduced precipitation rates (Pinto and Raible 2012), highlighting the importance of NAO impacts at the local scale. The third aim of this paper is to identify changes in magnitude and frequency in extreme precipitation events. Increases in extreme events have been detected at the national scale, in the frequency and magnitude of heavy rainfall events (Osborn et al. 2000a). This research will clearly contribute to better identification of climate change impact in West Cornwall, and will benefit policy makers developing strategies to identify regional areas at risk.

4.3 Cornwall

Cornwall is a county located in South West England covering an area of 3,653 km^2 (Fig. 11). A strong maritime effect is evident through a small range in annual mean temperature (9 °C), mild winter temperatures and among the highest wind speed rates in the United Kingdom. Winters are wet and summers dry with annual precipitation totals of 900–1,000 mm at the coast. Annual precipitation increases inland (up to 2,000 mm) and with higher altitude (Met Office 2011).

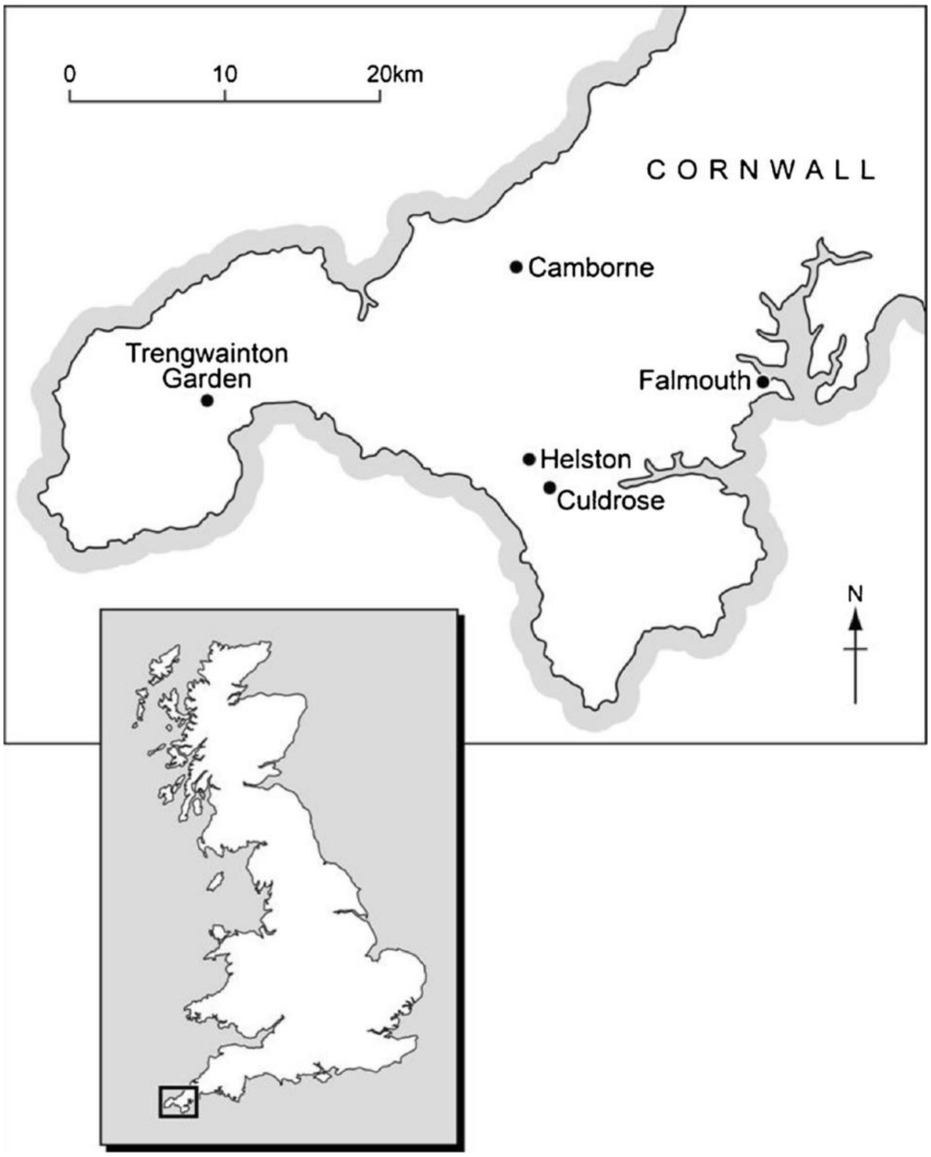

Figure 11 Weather stations in West Cornwall

4.4 Data and methodology

We analyse regional observational data series from the 19th century to the present. Table 3 shows the instrumental data analysed in this study. The majority of data sets required initial aggregation and digitisation from several archives: the UK Meteorological Office, the Royal Cornwall Polytechnic Society, Trengwainton Garden and Cornwall County Council Record Office.

Table 3 Weather stations-West Cornwall

Weather stations	*Location*	*Length of record*	*Temporal resolution*	*Altitude*	*Variables recorded*
Camborne station	50°13’0.4’’N 5°17’56’’W	1957-2010	Daily 9.00am	87 meters	Temperature Max/Min Precipitation
Trengwainton Garden	50° 7’38’’ N 5° 34’11’’W	1940-2010	Daily 9.00am	85 meters	Temperature Max/Min Precipitation
Culdrose	50°5’87’’N 5°15’22’’W	1985-2011	Daily 9.00am	76 meters	Temperature Max/Min Precipitation
Falmouth	50°9’05’’N 5°4’12’’W	1836-1952	Monthly	51 meters	Temperature Max/Min Precipitation
Helston	50°6’0’’N 5°15’0’’W	1843-1888	Monthly	35 meters	Temperature Max/Min Precipitation

Data for Camborne, Trengwainton Garden, Falmouth and Helston were obtained from archives and digitised. Data were quality checked twice for missing values, possible outliers (e.g. possible outliers on the plots were double checked with the archive documents to ensure they had not been entered erroneously) and inconsistency in the maximum and minimum temperature data (e.g. where minimum temperature was larger than maximum).

All data required conversion into modern units (°C and mm) achieved through automation in Microsoft Excel. The next step in pre-processing the data was to perform tests for homogeneity of variance. Homogeneity adjustment is a standard procedure in the analysis of historical weather data as changes in instruments, station location, measuring technique, or observational times may occur (Staudt et al. 2007; Brunet and Jones 2011), and these can cause trends in data independent of climate variability. Since we had a lack of nearby stations and therefore an inability to perform relative homogeneity analysis (Alexandersson 1986; Staudt et al. 2007; Firat et al. 2011), we applied absolute homogenization and tested homogeneity of variance within each station, using Levene, and Brown-Forsythe tests (Roth 1983; Caloiero et al. 2011; Martín et al. 2012). Prior to the trend analysis, years with one missing month for temperature records, were excluded from the analysis as well as the years with 10 % missing values for daily data. The same rule was used for the seasonal data. Seasons in this study were assigned in the following way: Winter-December, January, February

(DJF); Spring-March, April, May (MAM); Summer-June, July, August (JJA), and Autumn-September, October, November (SON). For precipitation records, the rule was to exclude all the years and seasons where data for the whole month were missing. This is because only in these months it can be assumed that there were no precipitation records. For trend detection Mann-Kendall and seasonal Mann-Kendall tests were used. Both are recognised as robust methods for the trend detection as normality of a distribution is not a requirement and missing values are tolerated, which is usually the case with instrumental data (Brunetti et al. 2000b; Burn and Hag Elnur 2002; Yue et al. 2002; Helsel and Frans 2006). The Mann-Kendall test detects monotonic positive or negative trends for annual means, where the seasonal Mann-Kendall test calculates the score for each season (Hess et al. 2001; Kahya and Kalaycı 2004). The Mann-Kendall statistic S is

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_j - x_k),$$

with

$$sgn\left(x_j - x_k\right) = \begin{cases} 1 \quad if \;\; x_j - x_k > 0 \\ 0 \quad if \;\; x_j - x_k = 0, \\ -1 \quad if \;\; x_j - x_k < 0 \end{cases}$$

where x_j and x_k are annual or monthly data values. As can be seen, S does not depend on the absolute values of data but on their directional change within a given period of time. S was used to formulate the test statistic Z as

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{VAR(S)}} \quad if \;\; S > 0 \\ 0 \quad if \quad S = 0, \\ \dfrac{S+1}{\sqrt{VAR(S)}} \quad if \;\; S < 0 \end{cases}$$

which was then tested using the two-tailed test with a required significance level α. The significance levels used in this paper were α=0.05, 0.01 and 0.001. A two-tailed test was performed for hypotheses H_0 (there is no significant trend in the data) and H_1 (there is a significant trend) at the chosen significance level α. The formula for variance of S is

$$VAR(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p\left(t_p - 1\right)\left(2t_p + 5\right)\right]$$

and accounts for ties in the data. Here n is the total number of data, q is the number of tied groups and t_p number of data values in the p^{th} group. The above formulae were applied on annual and seasonal means. For the Mann-Kendall on monthly means joined statistics S' and
VAR(S') were calculated from individual S_i and $VAR(S_i)$ for each of K=12 months as

$$S' = \sum_{i=1}^{K} S_i$$

and $VAR(S') = \sum_{i=1}^{K} VAR(S_i)$ and then tested for H_0 and H_1. A strong Z statistic (Z score) indicates there is a significant trend at the chosen α level without assuming how the trend is modelled. In order to calculate a magnitude of the trend, however, we need to assume a specific model of the trend. Here the magnitude of an assumed linear trend is estimated by Sen's slope estimator (Q score), a non-parametric version of linear regression (i.e. uses the difference between observed data and median value of y), (Salmi et al. 2002; Olofintoye and Sule 2010).

The correlation between instrumental data (annual and seasonal) and the NAO index was analysed by Spearman's rho non parametric test. As there are two types of NAO indices, the Station based and the Principal Component (PC) NAO index, we performed correlation for both. The station based NAO index is calculated from instrumental sea level pressure (SLP) for Lisbon and Stykkisholmur/Reykjavik with the records accessible further back in time, where the PC NAO index was calculated using an Empirical Orthogonal Function (EOF) of SLP anomalies over the Atlantic sector (i.e. 20°–80°N; 90°W–40°E) and presents more accurate movements of SLP anomalies (Lifland 2003; Hurrell and Deser 2009b). Changes in the frequency and magnitude of extreme precipitation events will be examined by return period analysis using the Gringorten formula (Fowler and Kilsby 2003).

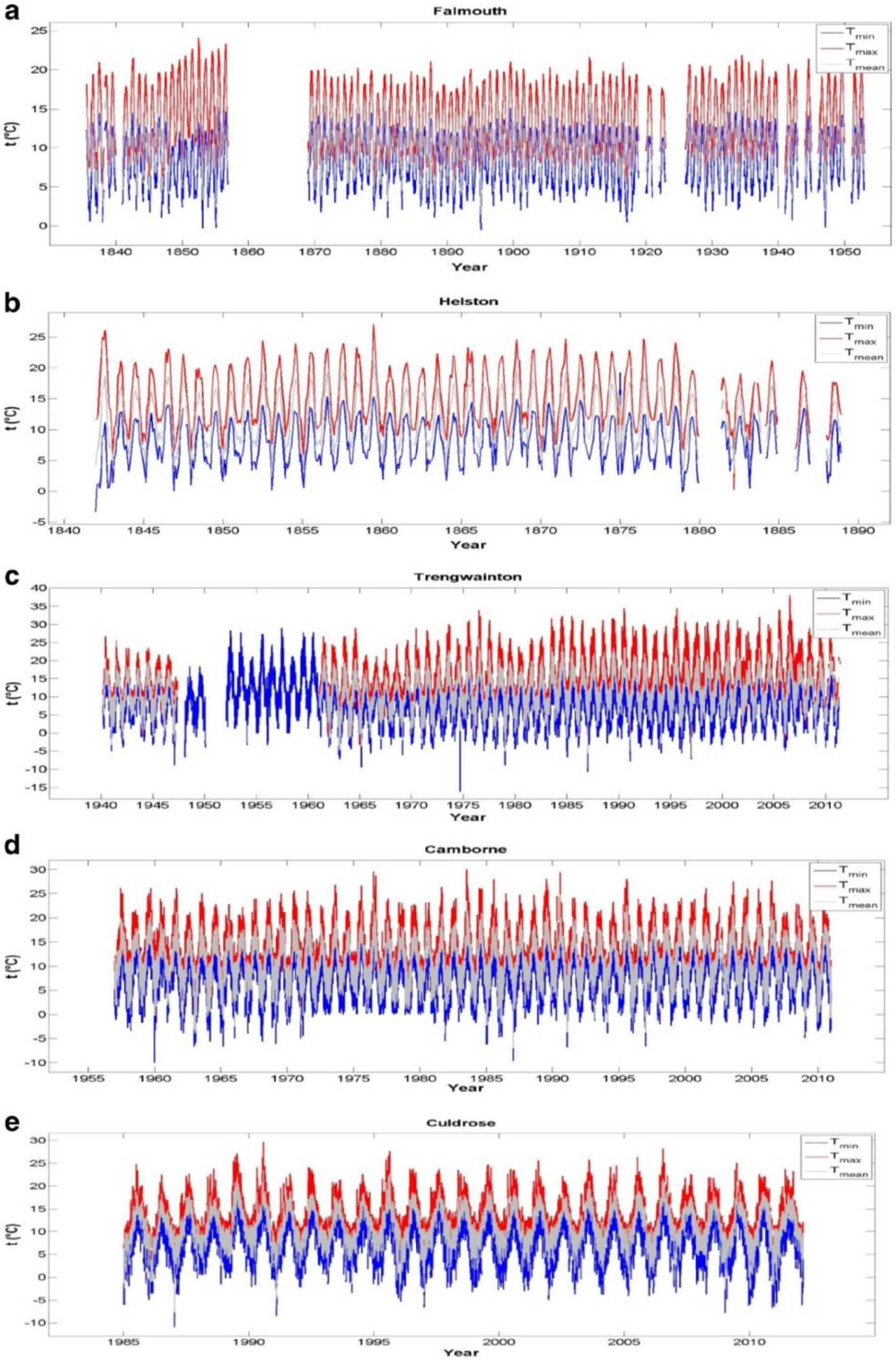

Figure 12 Time series of minimum (blue, Tmin), maximum (red, Tmax) and mean (grey, Tmean) temperatures from West Cornwall. Here Tmean = (Tmin + Tmax)/2. Plots (a) and (b) show monthly data for Falmouth and Helston, respectively. Plots (c) to (e) show daily data for Trengwainton, Camborne and Culdrose, respectively.

4.5 Results

4.5.1 Homogenization and trend analysis

Prior to trend analysis it was necessary to check whether the data met the homogenization standards, using Levene and Brown-Forsythe tests. The results for all stations and variables maximum temperature (Tmax), minimum temperature (Tmin) and precipitation (PPmm) showed there was no significant difference in the homogeneity of variance. As the time series were shown to be homogenous, no correction in the data was needed. Figure 12 presents the graphs of time series used in this study. To detect any positive or negative trends in climate variability over West Cornwall, Mann-Kendall tests were used and performed on monthly and yearly means for temperature and precipitation. This showed similar trends except for the data from Camborne and Culdrose. This is explained in detail below.

Table 4 shows the Mann-Kendall test results for presence of a statistically significant trend at the significance levels of 95 % (*), 99 % (**) and 99.9 % (***) for Falmouth (1835–1952), using yearly and seasonal data. Z scores show the strength and direction of the trend and Q is the slope of a linear Sen's estimate showing the annual decrease or increase in time series. The highest positive trends for Falmouth were detected for the autumn mean maximum temperature (Mean(T_{max}^{A})) with Z=3.15 and a yearly increase of 0.010 °C and for the annual mean maximum temperature (Mean(Tmax)) with Z=3.11 and the yearly increase of 0.008 °C (Fig. 13). These results differ from the observed national temperature increase, which are mainly recognised for summer maximum and winter minimum temperatures.

By splitting the Falmouth data and analysing the data for the 19th and 20th centuries separately, a positive trend was detected for the 20th century only in mean annual temperature Mean(T_{mean}), with Z=4.21 and yearly increase of 0.015 °C. The 20th century increase is even larger for the mean maximum annual temperature (Mean(T_{max})), with Z=5.42 and yearly increase of 0.026 °C. Large positive trends for the 20th century were detected for mean and maximum temperature in summer and autumn. However, seasonal temperatures in the 19th century showed decreasing trends in mean maximum spring temperatures (Mean(T_{max}^{SP})), Z=−2.12 with a yearly decrease of −0.021 °C and mean maximum summer temperatures, (Z=−2.12; Q=−0.020 °C). This is consistent with a cooling trend for the 19th century and a decrease in European summer temperatures shown elsewhere (Luterbacher et al. 2004a). However, another time series from the 19th century (Helston 1842–1879) showed positive trends for mean spring temperature and the mean autumn precipitation, although available data for this station covers a much shorter period (Table 4).

Mann-Kendall test results for Trengwainton Garden (1940–2010) data are presented at 95 % (*); 99 % (**) and 99.9 % (***) significance levels. A positive trend in annual data was detected for mean and maximum temperature, showing the largest trend rate in the mean maximum temperature (Mean (T_{max})), with Z=6.17 and annual increase of 0.096 °C (Table 4). A negative trend for annual data was detected for the mean minimum temperature (Mean(T_{min})) and mean precipitation (Mean(PPmm)). The largest positive trend, was for autumn maximum temperature (Mean(T_{max}^{A})), with Z= 6.04 and an annual increase of 0.082 °C. However, a negative trend was detected for the mean minimum spring temperature (Mean(T_{min}^{SP})),(Z=−3.15; Q=−0.035 °C) and the mean spring precipitation data (Mean($PPmm^{SP}$)), (Z=−3.05; Q=0.018 mm) (Fig. 14).

Table 4 Mann-Kendall results for Falmouth, Helston and Trengwainton Garden data, at 95 %(*), 99 %(**) and 99,9 %(***) significance level; Mean(Tmean)-Annual mean; Mean(Tmin)-Minimum temperature annual mean; Mean(PPmm)-Precipitation annual mean; Mean(Tmax)-Maximum temperature annual mean; Mean(TmeanW)-Monthly mean of Winter temperature; Mean(TmaxW)-Monthly mean of Winter maximum temperature; Mean(TmeanSP)-Monthly of Spring mean temperature; Mean(TminSP)-Monthly mean of Spring minimum temperature; Mean(TmaxSP)-Monthly mean of Spring maximum temperature; Mean(PPmmSP)-Monthly mean of Spring precipitation; Mean(TmeanSU)-Monthly mean of Summer temperature Mean; (TminSU)-Monthly mean of Summer minimum temperature; Mean(TmaxSU)Monthly mean of Summer maximum temperature; Mean(TmeanA)-Monthly mean for Autumn mean temperature; Mean(TminA)-Monthly mean for Autumn minimum temperature; Mean(TmaxA)-Monthly mean for Autumn maximum temperature; Mean(PPmmA)-Monthly mean of Autumn precipitation.

Falmouth 1835-1952	**Years**	**Test Z**	**Significance**	**Q**
Mean(T_{mean})	*1836-1952*	2.28	*	0.004
Mean(T_{max})	*1836-1952*	3.11	**	0.008
Mean(T_{min}^{SP})	*1835-1952*	2.14	*	0.006
Mean(T_{max}^{SP})	*1835-1952*	2.21	*	0.009
Mean(T_{mean}^{A})	*1835-1952*	2.59	**	0.006
Mean(T_{min}^{A})	*1835-1952*	2.49	*	0.006
Mean(T_{max}^{A})	*1835-1952*	3.15	**	0.010
Mean(T_{max}^{SP})	*1836-1900*	-2.12	*	-0.021
Mean(T_{mean})	*1901-1952*	4.21	***	0.015
Mean(T_{max})	*1901-1952*	5.42	***	0.026
Mean(T_{min})	*1901-1952*	2.23	*	0.007
Mean(T_{mean}^{SP})	*1901-1952*	3.24	***	0.023
Mean(T_{min}^{SP})	*1901-1952*	1.99	*	0.012
Mean(T_{max}^{SP})	*1901-1952*	3.85	***	0.032
Mean(T_{mean}^{SU})	*1901-1952*	3.40	***	0.024
Mean(T_{max}^{SU})	*1901-1952*	3.95	***	0.037
Mean(T_{mean}^{A})	*1901-1952*	3.34	***	0.024
Mean(T_{min}^{A})	*1901-1952*	2.16	*	0.017
Mean(T_{max}^{A})	*1901-1952*	3.86	***	0.033

Helston *1842-1879*	**Years**	**Test Z**	**Significance**	**Q**
Mean(T_{mean}^{SP})	*1842-1879*	2.30	*	0.033
				0.473
Mean(PP_{mm}^{A})	*1842-1879*	1.85	*	

Trengwainton G. *1940-2010*	**Years**	**Test Z**	**Significance**	**Q**
Mean(T_{mean})	*1941-1999*	4.86	***	0.049
Mean(T_{min})	*1941-1999*	-2.89	**	-0.033
Mean(T_{max})	*1941-1999*	6.17	***	0.096
Mean(PP_{mm})	*1941-2010*	-2.59	**	-0.012
Mean(T_{mean}^{W})	*1940-2004*	3.83	***	0.037
Mean(T_{max}^{W})	*1940-2004*	5.61	***	0.074
Mean(T_{mean}^{SP})	*1940-2000*	4.36	***	0.052
Mean(T_{min}^{SP})	*1940-2000*	-3.15	**	-0.035
Mean(T_{max}^{SP})	*1940-2000*	5.68	***	0.110
Mean(PP_{mm}^{SP})	*1940-2011*	-3.05	**	-0.018
Mean(T_{mean}^{SU})	*1940-1999*	4.30	***	0.053
Mean(T_{min}^{SU})	*1940-1999*	-2.73	**	-0.033
Mean(T_{max}^{SU})	*1940-1999*	5.39	***	0.112
Mean(T_{mean}^{A})	*1940-1999*	4.08	***	0.037
Mean(T_{min}^{A})	*1940-1999*	-2.69	**	-0.031
Mean(T_{max}^{A})	*1940-1999*	6.04	***	0.082

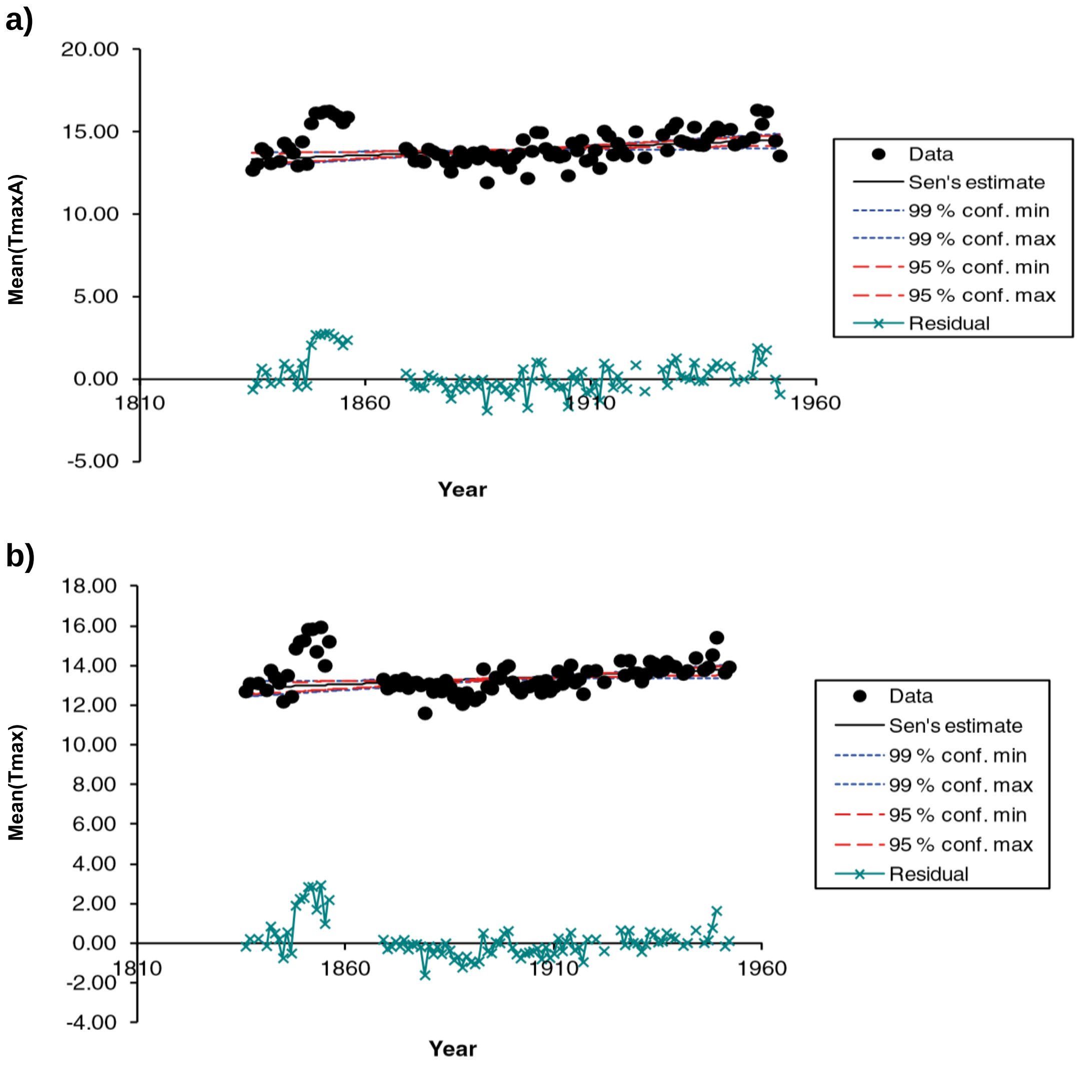

Figure 13 Trends for Falmouth a (Mean(TmaxA)) and b (Mean(Tmax)).

The observed decrease in spring minimum temperature and precipitation was opposite to the national estimates (Jenkins et al. 2009). All detected trends for Trengwainton Garden data are listed in Table 4.

The Mann-Kendall results for Camborne station (1957–2010) at the 95 % (*) and 99 % (**) significance levels are presented in Table 5. All annual trends showed an increase in the mean temperature (Mean(T_{mean})); mean minimum temperature (Mean(T_{min})) and mean maximum temperature (Mean(T_{max})). This is different from the Trengwainton Garden annual results (Table 4). The largest positive trend for the seasonal values was in the mean summer minimum temperature (Mean(T_{min}^{SU})), (Z=2.97;Q= 0.016 °C) (Fig. 15). Again, in relation to Trengwainton data, we report directionally opposite trend in mean summer minimum temperatures. Here monthly Mann-Kendall test has detected a negative trend in mean precipitation where the annual Mann-Kendall test has not detected it.

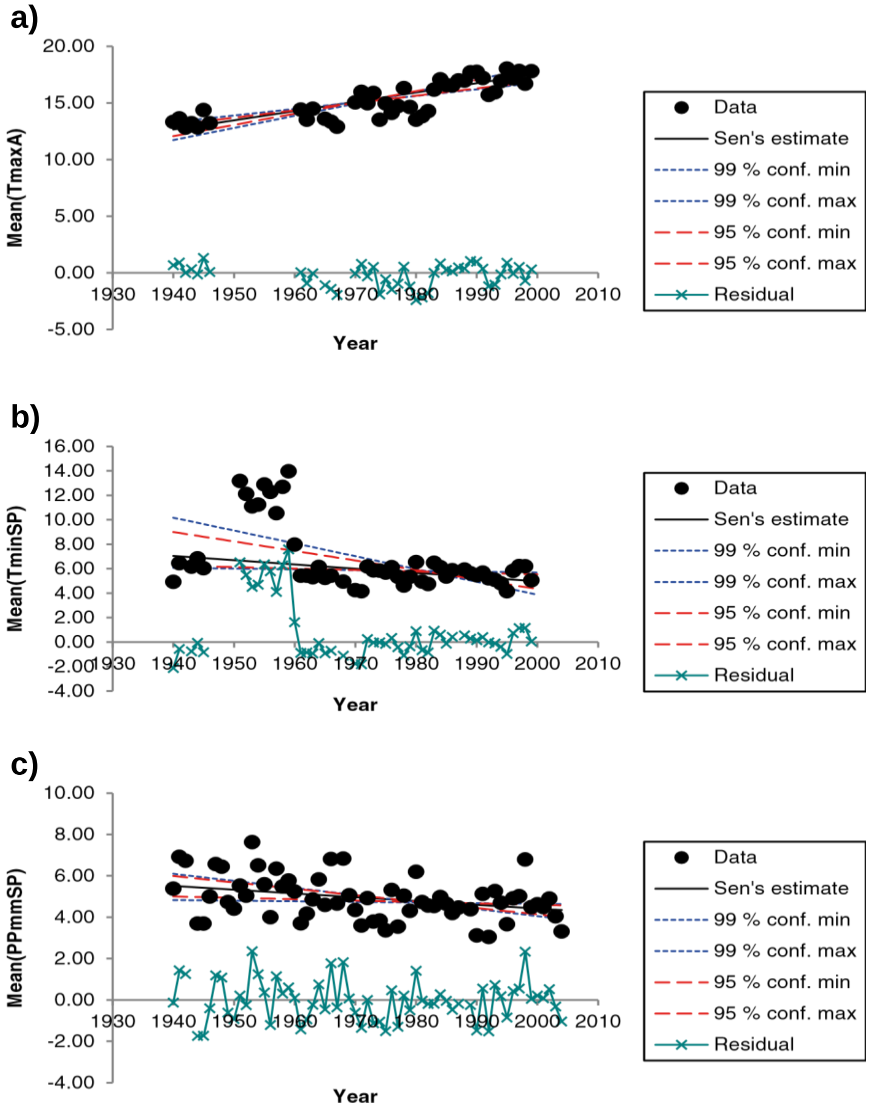

Figure 14 Trends for Trengwainton a (Mean(TmaxA)), b (Mean(TminSP))and c (Mean(PPmmSP)).

The Mann-Kendall results for Culdrose station (1985–2011), which has the shortest available record for the 20th century and the past decade, detects positive and negative trends at the; 95 % (*) and 99 % (**) significance level (Table 5). The largest positive trend for annual data was detected for mean maximum autumn temperature

(Mean(T_{max}^{A})), Z=2.59 with an annual increase of 0.053 °C. The largest negative trend was calculated for mean precipitation (Mean(PPmm)), Z= −2.59 and annual decrease by 0.034 mm. It is interesting to observe that the Mann-Kendall test detects a decrease in mean winter precipitation (Mean(PPmm^{W})), Z=−1.67, of −0.045mm (Fig. 16). There was no trend in summer precipitation. However the Mann-Kendal test computed with the monthly data showed additional positive trends in mean and minimum temperatures.

Table 5 Mann-Kendall results for Camborne and Culdrose at 95 %(*), 99 %(**) and 99,9 %(***) significance level. ^{1}Mann-Kendall test computed with monthly data; Mean(Tmean)-Annual mean; Mean(Tmin)-Minimum temperature annual mean; Mean(Tmax)-Maximum temperature annual mean; Mean(PPmm)-Precipitation annual mean; Mean(TmeanSP)-Monthly of Spring mean temperature; Mean(TminSP)-Monthly mean of Spring minimum temperature; Mean(TmaxSP)-Monthly mean of Spring maximum temperature; Mean(TmeanSU)-Monthly mean of Summer temperature; Mean; (TminSU)-Monthly mean of Summer minimum temperature; Mean(TminA)-Monthly mean for Autumn minimum temperature; Mean(TmaxA)-Monthly mean for Autumn maximum temperature.

Camborne ***1957-2010***	**Years**	**Test Z**	**Significance**	**Q**
Mean(T_{mean})	*1957-2010*	2.69	**	0.013
Mean(T_{min})	*1957-2010*	2.74	**	0.016
Mean(T_{max})	*1957-2010*	2.01	*	0.010
Mean(PP_{mm})^{1}	*1957-2010*	-2.10	*	-0.009
Mean(T_{mean}^{SP})	*1957-2010*	2.61	**	0.018
Mean(T_{min}^{SP})	*1957-2010*	2.44	*	0.020
Mean(T_{max}^{SP})	*1957-2010*	2.39	*	0.015
Mean(T_{mean}^{SU})	*1957-2010*	2.18	*	0.012
Mean(T_{min}^{SU})	*1957-2010*	2.97	**	0.016
Culdrose ***1985-2011***	**Years**	**Test Z**	**Significance**	**Q**
Mean(PP_{mm})	*1985-2011*	-2.59	**	-0.034
Mean(T_{mean}^{A})	*1985-2011*	2.33	*	0.054
Mean(T_{min}^{A})	*1985-2011*	2.13	*	0.052
Mean(T_{max}^{A})	*1985-2011*	2.59	**	0.053
Mean(T_{mean})^{1}	*1985-2011*	3.27	***	0.024
Mean(T_{min})^{1}	*1985-2011*	3.08	***	0.027

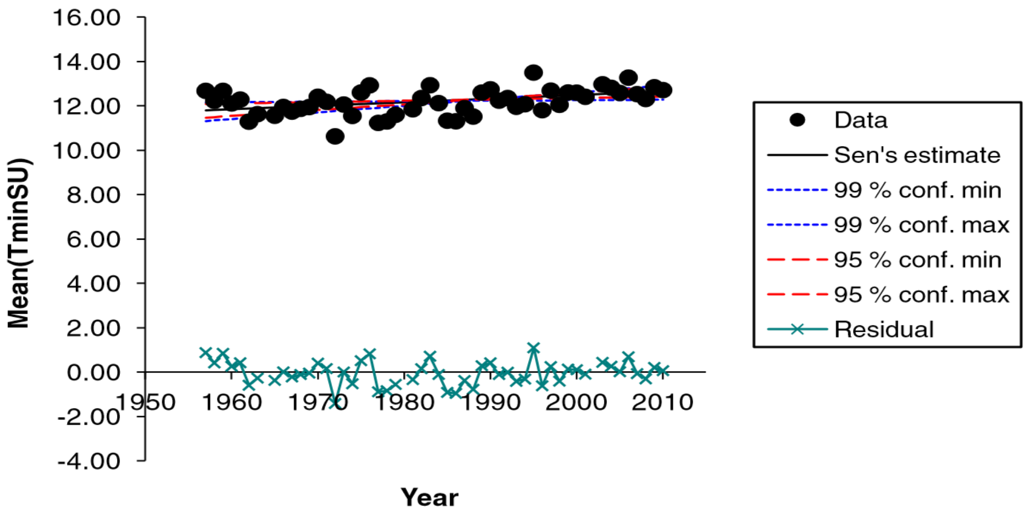

Figure 15 Trend for Camborne (Mean(TminSU))

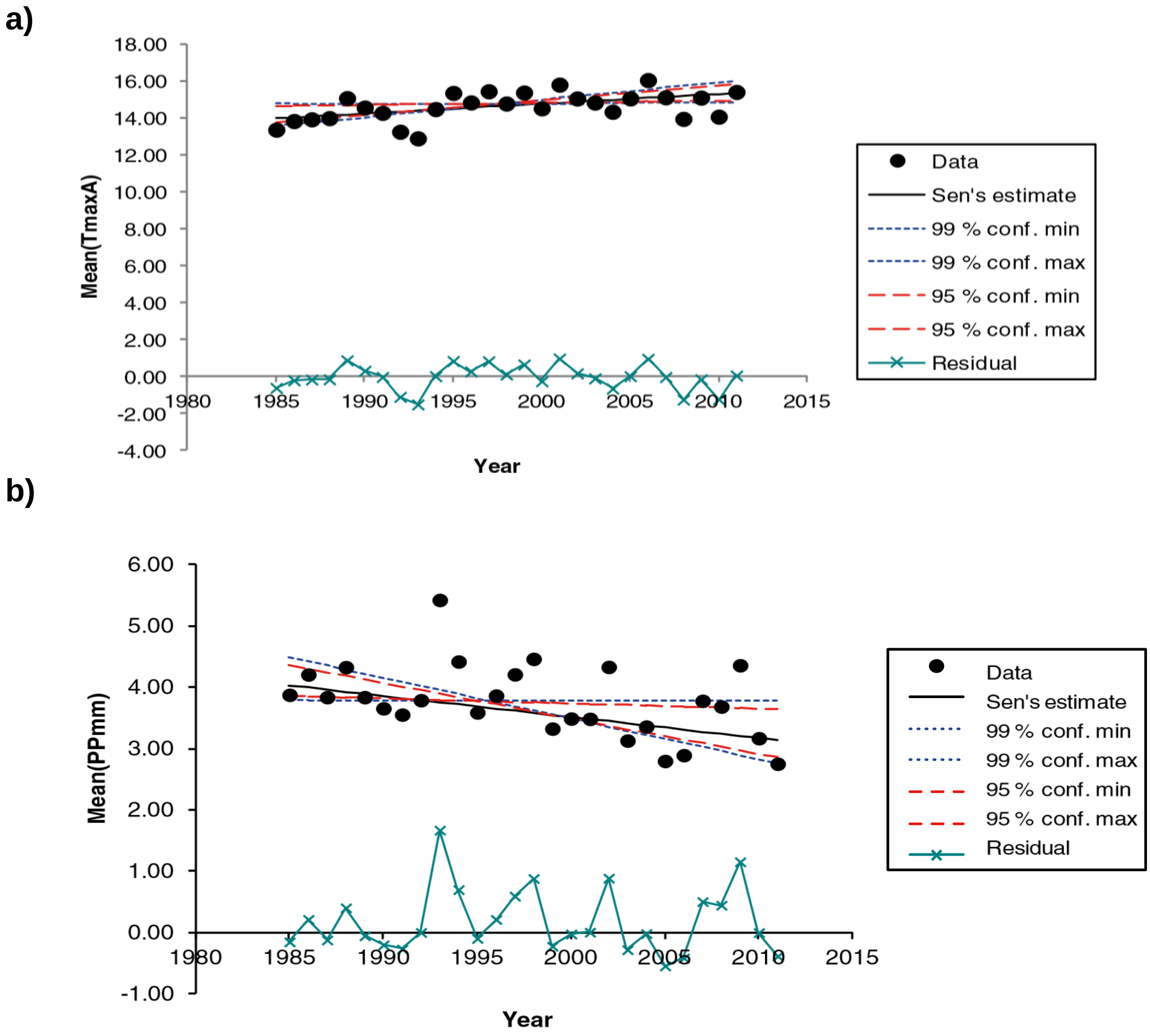

Figure 16 Trends for Culdrose (a) (Mean(TmaxA)) and b (Mean(PPmm))

Table 4 Spearman's rho correlation results for West Cornwall

4.5.2 North Atlantic Oscilation (NAO) correlation

Correlation between NAO indices (station and PC based) and climate variables (Tmean, Tmin, Tmax and PPmm), from the five stations was assessed. The impact of the NAO on England's seasonal climate has been recognised (Hurrell and Van Loon 1997; Murphy and Washington 2001); hence we correlated seasonal averages, winter (DJF), spring (MAM), summer (JJA) and autumn (SON). As climate variables in this study are nonparametric we use Spearmans's rho correlation. Results for both NAO indices (NAO PC and NAO station) are calculated and presented in Table 6 where r is correlation coefficient and p is significance level (95 %). However, for the Helston station, correlation was performed just with the station base NAO index as data are available from 1865, whereas data for the NAO PC index are available from 1889 (Hurrell 2012). Results for Falmouth, Camborne, Culdrose and Trengwainton showed the largest positive correlation for winter mean and minimum temperature consistent with the NAO impact in Northern European winter temperatures. A possible reason for differences in r values between sites is fluctuations in positive and negative mode of NAO index. However, there is no positive correlation between winter season and precipitation. The spring season showed positive correlation for Tmean, Tmax and Tmin in all stations except Helston. Furthermore negative correlation for precipitation was detected for the summer season in all stations except Helston. The latter showed negative correlation for precipitation in spring whereas Camborne precipitation showed a positive correlation for autumn. This correlation may be explained by the fact that the NAO index has the largest amplitude between November and April (Stenseth et al. 2003), including winter and parts of autumn and spring seasons. Winter and spring season showed more significant correlation, with both NAO indices, where summer showed correlation with the single index.

Table 6 Spearman's rho correlation results for West Cornwall.

Station / Variable		*NAO index*	Winter		Spring		Summer		Autumn	
			r	**p**	**r**	**p**	**r**	**p**	**r**	**p**
Falmouth (1865-1952)	*Tmean*	*PC*	0.364	0.024	0.350	0.020	0.418	0.004		
		Station	0.398	0.000	0.343	0.002				
	Tmax	*PC*					0.450	0.001		
		Station	0.396	0.000	0.304	0.007			0.264	0.022
	Tmin	*PC*	0.344	0.034	0.324	0.029				
		Station	0.362	0.002	0.320	0.005				
	PPmm	*PC*	-0.316	0.044			-0.328	0.024	0.310	0.032
		Station								
Camborne (1957-2010)	*Tmean*	*PC*	0.562	0.000	0.279	0.044	0.315	0.023		
		Station	0.602	0.000						
	Tmax	*PC*	0.532	0.000	0.313	0.023	0.424	0.001		
		Station	0.606	0.000						
	Tmin	*PC*	0.588	0.000						
		Station	0.590	0.000						
	PPmm	*PC*					-0.478	0.000		
		Station			0.276	0.047				
Culdrose (1985-2011)	*Tmean*	*PC*	0.625	0.000	0.500	0.008				
		Station	0.659	0.000						
	Tmax	*PC*	0.516	0.005	0.422	0.029	0.392	0.042		
		Station	0.559	0.002						
	Tmin	*PC*	0.637	0.000	0.439	0.022				
		Station	0.697	0.000						
	PPmm	*PC*					-0.480	0.011		
		Station								
Trengwainton (1940-2010)	*Tmean*	*PC*	0.584	0.000	0.322	0.037				
		Station	0.594	0.000						
	Tmax	*PC*	0.611	0.000	0.358	0.019				
		Station								
	Tmin	*PC*	0.294	0.024						
		Station	0.337	0.009						
	PPmm	*PC*	-0.318	0.007			-0.321	0.007		
		Station								
Helston (1865-1889)	*PPmm*	*PC*								
		Station			-0.467	0.038				

4.5.3 Return period analysis

The third aim of this paper was to identify changes in the intensity of extreme precipitation events as one of the major climate change impacts (Kharin et al. 2007). The return period analysis has been used to analyse magnitude and frequency of extreme weather events (wind and precipitation) (Makkonen 2006). This analysis was conducted by the Gringorten Plotting Position formula using precipitation data for 24 h periods from Camborne and Trengwainton Garden stations. Culdrose station is excluded from this analysis due to shorter length of time series. Camborne and Trengwainton data were split into two periods: pre-1975 and post-1975, regarding the time series duration and statistically significant difference between two periods tested with Mann Whitney U. Our results of return period analysis showed a decrease in intensity of extreme events (Fig. 17a and b). Return periods for Camborne indicate higher intensity of precipitation events (above 27 mm) in the pre-1975 period. For example; a 50 mm event (24 h period) in pre-1975 occurred every 3.15 years, whereas the same event in post-1975 occurred every 5.40 years (Fig. 17a). This is different to popular estimations of increasing frequency and intensity of extreme events. Return periods from Trengwainton Garden showed higher intensity of extreme events in the post-1975 period up to 60 mm. However, more of >60 mm intensity events were detected in the pre-1975 (Fig. 17b). Also 80 mm events happened more often (every 11.77 years) in pre-1975 and in post 1975 every 53.79 years.

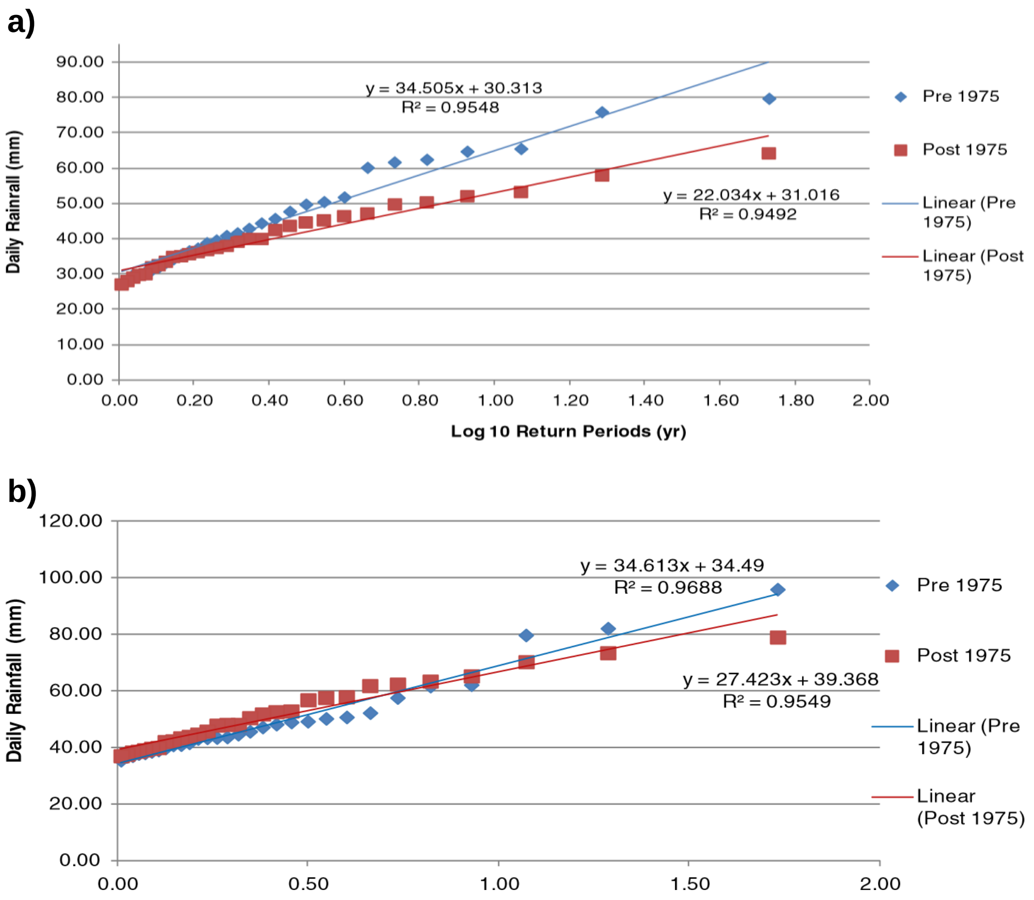

Figure 17 Return periods for daily data: a Camborne and b Trengwainton Garden

4.6 Discussion

This study illustrates the importance of archive records in the assessment of historical climate change research. Temperature and precipitation analysis over West Cornwall suggested positive trends in both the 20th and 21st century for annual and maximum temperature. There were no positive annual trends for data from the 19th century (in Falmouth and Helston). However trends in annual and seasonal temperature and precipitation in the 19th, 20th and 21st centuries differed locally. The largest seasonal positive trends were found in the 20th and the present century, and were detected for maximum and mean temperatures in autumn. This was followed by maximum spring and summer temperatures. The highest variability in seasonal temperatures within one station was detected for Trengwainton Gardens. In this station positive trends were also detected in maximum and mean winter temperatures, as well as negative trends in minimum summer temperatures. These results are generally consistent with the national projections (Jenkins et al. 2008). Furthermore, precipitation results showed opposite trends than those estimated at the national scale. All stations from the 20th and 21st century show negative trends in precipitation. Similarly, correlation with NAO index showed negative results, which is opposite to the spatially larger scale understanding of index positive mode and higher precipitation rates (Hurrell and Van Loon 1997; Stenseth et al. 2003). However correlation with NAO showed positive results for winter and spring temperatures in all stations except Helston. When performing NAO index correlation it is important to use both NAO indices as it is shown that correlation could be excluded when actually present. To conclude a statistically significant correlation with NAO index is detected and differs locally and seasonally. This shows that further research on the temporal and spatial variability of NAO will allow better understanding of seasonal temperature variability over West Cornwall. Return period analysis showed a decrease in intensity and frequency of extreme events as well as its high spatial variability over West Cornwall.

4.7 Conclusion

This study clearly shows how local climate change research is important as trends found in localities can vary from national and global estimates. Our work shows local differences in the temperature and precipitation variability over West Cornwall, and local differences in NAO correlation. These results are vital for our future research which will track vegetation responses to these changes in West Cornwall using historic and current vegetation records. This will help in developing better adaptation and conservation strategies as well as further understanding how climate change can affect ecosystem services in West Cornwall. Future research should focus on climate variability in other areas (wherever long term instrumental data are available) and biodiversity response to climate change. From this appropriate mitigation and conservation strategies can develop to protect biodiversity from climate change.

5. Plant species responses to climatic variability on the west Cornwall peninsula (South West England)

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Author contributions:

A. Kosanic conceived and designed the experiments, formulated the research hypotheses (with guidance from KA and SH). AK and TT analysed the data. KA, SH, TT, JB and AK co-wrote the paper but the writing was led by AK with iterative comments and input from other authors.

5.1 Abstract

Here we track vegetation distribution and change in West Cornwall (South West England) using historical and recent vegetation records and assess the use of Ellenberg and environmental indicator values as indicators of environmental change. We used botanical records from a historical Flora published in 1909 (Davey's "Flora of Cornwall") and contemporary data available online. Both data sets were geo-referenced using GIS and the change in species distribution was analysed. Loss of range was detected for 18 species with 6 species losing more than 50% of their previous at the 10km grid scale. Statistical tests showed that Ellenberg and environmental indicator values could be used as environmental change indicators. Significant correlations occurred between range loss and in species optimum January temperatures, precipitation, moisture, light and nitrogen values.

5.2 Introduction

Changes in temperature and precipitation over the past 40 years have triggered changes in vegetation distribution (Root et al. 2003; Thuiller et al. 2005b). Rapid increases in global temperatures, even with the most optimistic IPCC emissions scenario suggest a projected increase in global temperatures of 1.8°C by the end of the 21st century with likely negative impacts on many plant species (Chapin Iii et al. 2000; Davis and Shaw 2001; IPCC WG1 4AR 2007; IPCC WG1 5AR 2013a). Changes in temperature and precipitation are highly spatially and temporally heterogeneous having different ecological effects in different regions (Walther et al. 2002). As a result, research focused on analysing vegetation responses to these changes at local and regional scales is needed.

Historical herbarium collections and records describing past distributions of plant species are of exceptional scientific value because they offer the means of tracking changes in species' geographic distribution and sometimes phenology, leading to better conservation strategies for endangered species (Ponder et al. 2001; Primack et al. 2004; Graham-Taylor et al. 2009; Rivers et al. 2011). One major obstacle to this is their lack of precise geo-referenced information (Graham et al. 2004). A major challenge for museums and archives is to make these data available through databases in a geo-referenced form (Guralnick et al. 2006). Furthermore, historical (pre 20th century) records are rarely collected systematically with equal effort across geographic space, so the absence of a record from a particular locality does not imply that a particular species was not present. Attribution of vegetation responses to climate change is difficult because decadal changes in vegetation distribution are often related to non-climatic factors such as land use change (Parmesan and Yohe 2003). Hence, more information on vegetation responses to climate variability is needed to guide policy makers and future conservation strategies.

Here we examine changes in the geographical distribution of plant species in West Cornwall, UK (pre-1900 and post-1900) using records from a historic flora and contemporary observations. We assess whether Ellenberg values (Hill et al. 2004) can be used as a tool for causality detection, between the spatial distribution of individual plant species and climate change by addressing two questions:

1. Can historical vegetation data be used to evaluate climatic effects on vegetation responses? This requires comparison between historical vegetation data from pre-1900 (Davey 1909) and current records (Preston et al. 2002).
2. Is there a correlation between Ellenberg values of key plant species and spatial patterns of change in their geographical distribution over this time period? Here, the abiotic drivers of observed changes in plant species distribution were evaluated using Ellenberg indicator values (Hill et al. 2004).

5.3 Data and Methodology

5.3.1 Contemporary vegetation data

Contemporary spatial records describing species distribution were obtained from the online database, of the National Biodiversity Network (NBN 2013), consisting mostly of records from the "New Atlas of the British and Irish Flora" (Preston et al. 2002) showing the late 20th century geographical distribution of plant species in West Cornwall in 10 km grids. These data were and imported into ArcGIS. In the rest of the paper, these data are referred as (post-1900).

5.3.2 Historical vegetation data

In this research historical vegetation data were used from "The Flora of Cornwall" (Davey 1909), a collection of all known herbarium data in the county of Cornwall and Scilly Isles from the 18th, and 19th centuries. In the historic records, Cornwall was divided into eight botanical districts, based on river basins in Cornwall (Davey 1909). Geo-referenced data were from the 5th, 6th, 7th and 8th districts in West Cornwall (Fig. 18). Records contained native and non-native species. As historical data contains textual descriptions of localities where plant specimens were found (e.g. "*Achillea ptarmica*, first record: 1769; district 7: Porkellis Moor, Wendron, Coverack, *Emyln"*) (Davey 1909) page 247), rather than explicit definitions of longitude and latitude, we acknowledged several uncertainties in the geo-referencing process (taxonomical inaccuracy, spatial error, bias associated with the frequency and time spent on data collection (areas or species could be poorly sampled)). This latter uncertainty provided particular challenges (Graham et al. 2004), however all uncertainties are explained in 5.3.3 section.

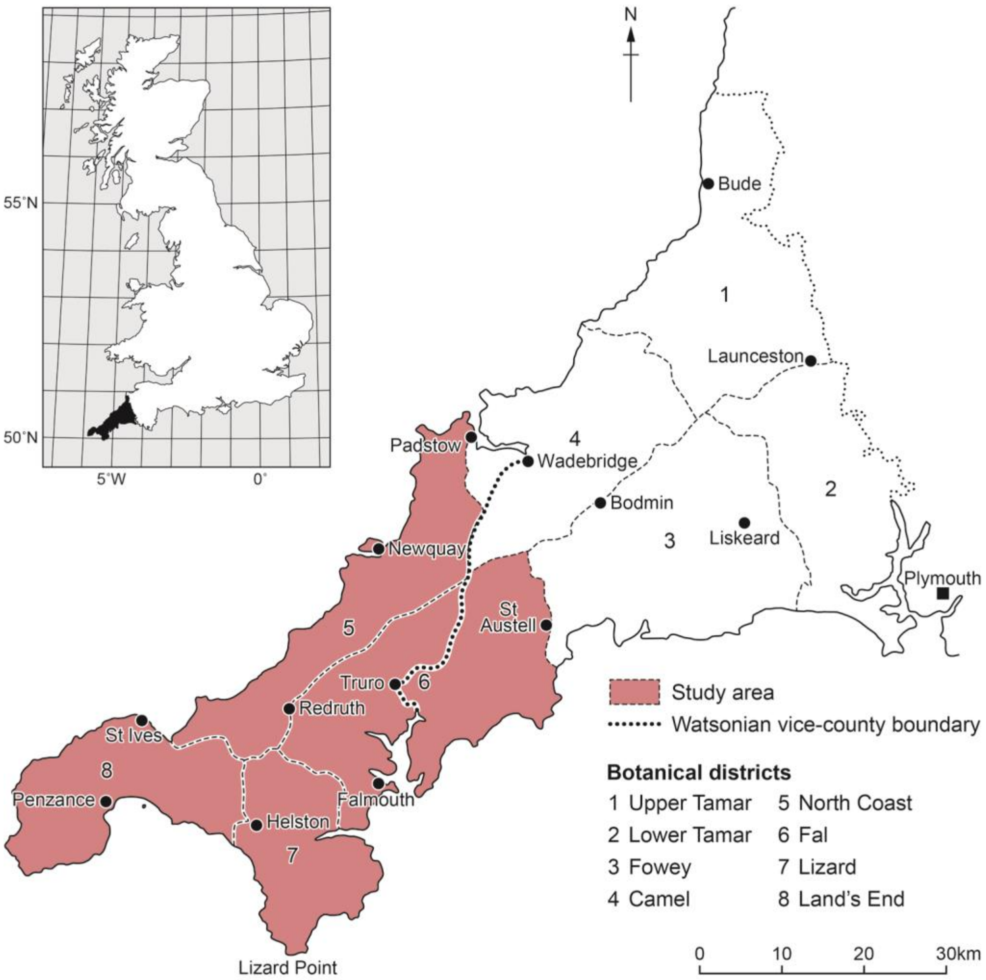

Figure 18 Botanical districts used in this study

5.3.3 Handling and analysis of vegetation records in ArcGIS

For historical data, importing into GIS posed methodological challenges (Guralnick et al. 2006). “The Flora of Cornwall” (Davey 1909) contains descriptions of species (genus and specific epithet) and localities where specimens were collected, and in order to import them to GIS three steps were undertaken.

1. For this study 381 species were selected, representing native and alien species, which were also selected from the New Atlas of British and Irish Flora (Preston et al. 2002). Species without published Ellenberg values were excluded from the analysis. An electronic database was constructed from these data and formed the basis for the study.
2. Chosen species were then cross-checked in “The Flora of Cornwall” (Davey 1909) and these records were located as accurately as possible using Google Earth and cross-checked with online Ordnance survey maps (OS 2010). Specimens which were found to have very ambiguous locality descriptions (e.g. “West Penwith” – which covers a large area), or incorrect taxonomy were excluded from the data base and the analysis which was consistently followed. 1274 plant specimens from West Cornwall were geo-referenced.
3. Data were imported into ArcGIS and the extent of uncertainty was calculated and a uniform value (i.e. uncertainty around each point) was applied to every record. A point radius method was used to represent this uncertainty (Wieczorek et al. 2004). To arrive at a suitable radius size to best represent this uncertainty, a maximum distance (from the centre of the locality to their furthest end) for 50 random species localities was established using Google Earth. Then the upper quartile of this uncertainty was calculated and found to be 1.5 km. This value was used as an uncertainty radius around the location of each specimen and buffered around each point in GIS (Fig. 19). As historical maps from the same period of specimens collection were not available for radius calculation and clearly the extent of the places changed throughout history (Wieczorek et al. 2004; Garcia-Milagros and Funk 2010), our uncertainty radius is more likely to be an overestimate than underestimate. Upon creation of uncertainty buffers, they were attributed to the spatial joints of 10 km grid cells in West Cornwall.

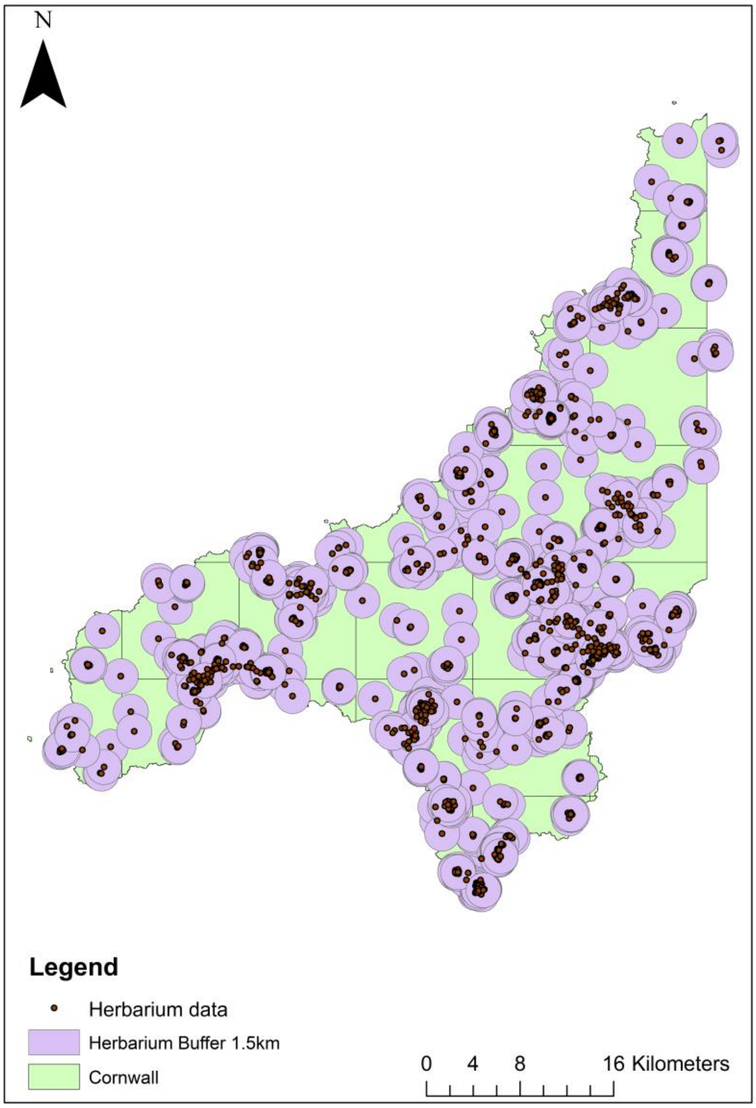

Figure 19 Historical vegetation data with 1.5 km uncertainty buffers.

Finally all data for each species were combined to produce a dataset describing the historic distribution of the selected plant species in West Cornwall and repeated for contemporary data. We used ArcGIS to map the presence of historical and current data in 10 km grid cells. Changes in the geographical distribution of plant species were then analysed, allowing the calculation of the difference in area covered as a proportion of the past and to understand changes in geographical coverage of individual species. We note that while contemporary records have been collected systematically in order to map species ranges, historical records may be absent for locations where the species was present. For this reason we concentrated on losses in geographical range at the 10 km scale (where a species was historically recorded in areas where it was not previously found) and have not considered apparent gains (where a species was not historically recorded but is now found to be present). However in making the comparison with the analysis from “Change in the British Flora 1987-2004” (Braithwaite et al. 2006), we present decreased or increased (Red list species) species with coverage over 50%.

5.3.4 Analysis of plant species Ellenberg and environmental indicator values and geographical distribution change

Ellenberg values are available for most central European plant species and are based on field observations showing species sensitivity to seven environmental factors (T-temperature, L-light, M-moisture of soil, R-reaction, S salt concentration, K-continentality and N- nitrogen (soil fertility)), (Godefroid and Dana 2007). Ellenberg values are related to the species synecological optimum (species interactions with the environment) rather than ecological ones (Pignatti et al. 2001). Environmental variables were calibrated for the UK and scaled between 1-9 or 1-12 for each species (e.g. M=1 indicator of extreme dryness where M= 12 indicates plant almost constantly under water), (Hill et al. 2004). Ellenberg values have been widely used for environmental and ecological monitoring (Schaffers and Sýkora 2000; Pignatti et al. 2001; Diekmann 2003; Muller 2010; Renetzeder et al. 2010; Reger et al. 2011; Häring et al. 2012).

In this study, six indicators were analysed; three Ellenberg-derived and three climatic indicators (referred here as Environmental indicator values), where data were derived from mean climatic values of the 10 km grid cells for the British Isles (Hill et al. 2004):

- January temperature (Tjan)
- July temperature (Tjul)
- Precipitation (RR)
- Ellenberg value for light (L)
- Ellenberg value for moisture (M).
- Ellenberg value for nitrogen (N)

For each indicator, three properties were investigated. These were mean change in overall range at 10 km resolution, the percentage range expansion (i.e. the area that was not recorded pre-1900, but for which recent records exist), and the percentage range contraction (i.e. the area that was occupied pre-1900 but unrecorded in recent records). To match the ordinal values for the three Ellenberg indicators, the temperature and precipitation indicators (Tjan, Tjul and RR) were divided into groups. The species were divided into 8 equal-sized groups with group 1 being the coldest/driest and group 8 the warmest/wettest. To determine if any of the changes were significantly different depending on the value of the indicator, the Mann-Whitney U-test was used with p value set at < 0.05. It was also used to determine the significance of the difference between indicator values of past and present only species.

5.4 Results

5.4.1 GIS analysis on change in plant species geographic distribution over West Cornwall

The research analysed 123 plant species from pre-1900 and 129 plant species that were found post-1900 over West Cornwall. Overlap in these two groups gave 116 species, as some species only appeared in one instance, or they did not have an intersect (Fig. 20). Overall change within these overlap species showed a decrease in geographic distribution for 18 species (in 6 species decrease was larger than 50%) and no change in geographic distribution for 10 species. Table 7 shows species with the highest loss in the area of West Cornwall.

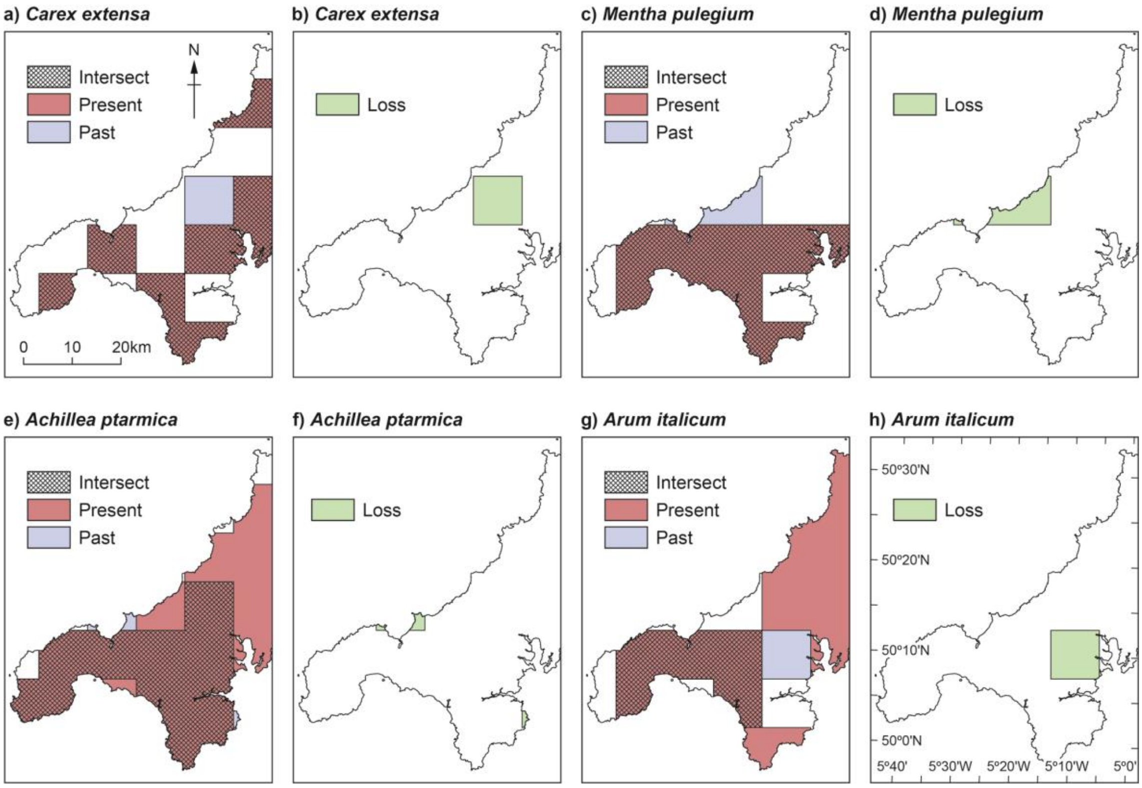

Figure 20 a) Past and present geographical distribution and their overlap/intersect for a) *Carex extensa* b) Loss for *Carex extensa* ; c) Intersect for *Mentha pulegium*; d) Loss for *Mentha pulegium*; e) Intersect for *Achillea ptarmica* f) Loss for *Achillea ptarmica*

Table 7 Species with the highest apparent range loss (in terms of areal coverage) in Cornwall.

Species loss	***Km*^{2}**
Anagallis arvensis subsp. foemina	484
Anthemis cotula	452
Campanula rotundifolia	325
Clinopodium acinos	929
Cystopteris fragilis	611
Genista anglica	217
Juncus maritimus	257
Lavatera cretica	210
Linum usitatissimum	212
Medicago sativa subsp. falcata	469
Scilla autumnalis	327

In total there were 37 species included in the Red List (IUCN 2014), and BAP-United Kingdom list (JNCC 2010), and 16 of these species showed an increase or decrease in the dataset describing present distribution (i.e. post-1900) over 50%. However in comparison with the change in vegetation at the national scale analysed between 1987 and 2004 (Braithwaite et al. 2006), we indicate different results (Table 8), suggesting that changes at the end of the 20th and beginning of the 21st centuries differed from changes observed during the 19th to 20th centuries.

Table 8 Red List Species and BAP species, their increase and decrease and comparison with the "Change in the British Flora 1987-2004"(Braithwaite et al. 2006; IUCN 2014).

Red list species and BAP	***Increase/Decrease in Geographical distribution in West Cornwall (%)***	***Change in the British Flora 1987-2004***
Allium ampeloprasum	+ 317	No data
Carex distans	+208	Increase
Clinopodium acinos	- 80	Decrease
Cyperus longus	+ 179	No data
Equisetum fluviatile	+ 147	Decrease
Juniperus communis	+ 688	Decrease
Lycopodiella inundata	- 21	No data
Lycopodium clavatum	0	Increase
Lysimachia vulgaris	+ 424	Increase
Ranunculus arvensis	+ 31	No data
Ranunculus tripartitus	+ 268	No data
Vicia bithynica	+ 199	No data

5.4.2 Ellenberg and Environmental indicator values

Based on the Ellenberg (EV) values and environmental indicator values (EIV), a wide range of species have been observed in West Cornwall (Table 9). Nearly the full range of values for L, M and N Ellenberg values were present as well as for the ranges of temperature and precipitation indicator values are shown in Table 9. As most of the species were observed in the past (pre-1900) and present (post-1900), the range of each of the indicators is similar for both periods.

Table 9 The minimum, median and maximum value for each of the Ellenberg and Environmental indicator values.

Ellenberg and Environmental Indicator Values	*Minimum*	*Median*	*Maximum*
January Temperature (Tjan)	1.9°C	3.8°C	6.7°C
July Temperature (Tjul)	13°C	15.5°C	16.6°C
Precipitation (RR)	604mm	914mm	1483mm
Light (L)	3	7	9
Moisture (M)	2	5	12
Nitrogen (N)	1	6	9

For the remaining 121 species, the changes in area are shown in Figure 21 and 22. For the first three indicators, there are few significant differences in the overall area change between EV and EIV. Species with Tjan=3 (top left in Fig. 21), have a smaller percentage increase in area than the warmer species, Tjan=4 and Tjan=7. For the RR indicator, group 6 is significantly higher than 3. The extreme groups (1, 2, and 7, 8) are similar. For Tjul there are no significant differences between indicators for changes in overall area. Therefore, based on overall percentage increase in area, species with higher January temperatures tend to have a larger increase than colder species. Using precipitation, species with a slightly higher P value have the biggest increase (top right, Fig. 21).

Based on the old area that disappeared (middle row Fig. 21), there are few significant differences based on temperature indicators. Only the species with Tjan=1 are significantly greater than those with Tjan = 3. For precipitation, the species with the extreme indicator values (RR = 1, 2 and 8) have a significantly greater loss in area than those with RR = 6.

For the area that was new coverage (bottom row, Fig. 21), there were no overall significant differences based on the summer temperature and precipitation indicators. For the January temperatures, those with Tjan=3 have a smaller percentage of new area compared with Tjan= 2, 4, 7, and 8. There were no other significant differences.

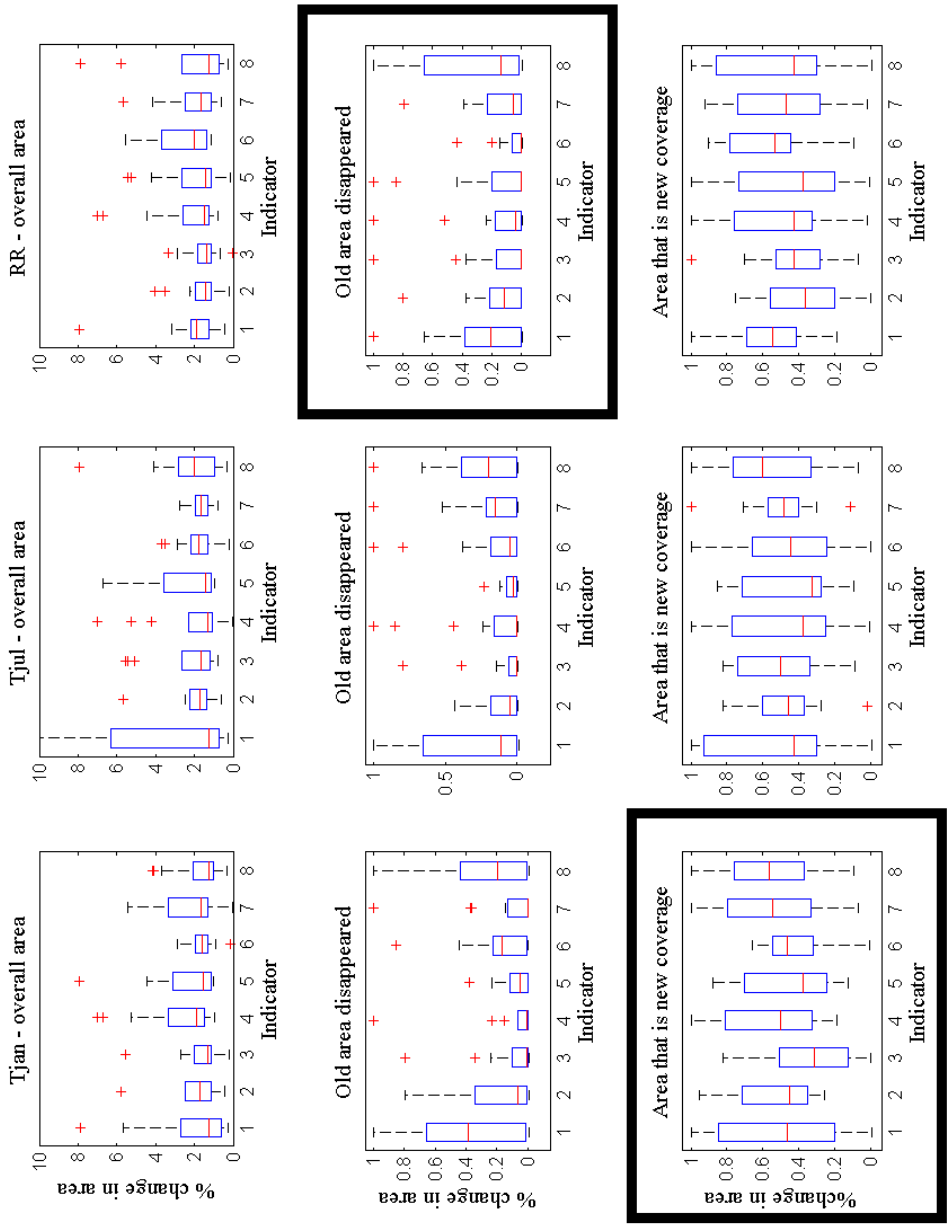

Figure 21 Percentage change in area for total area (top), old area that disappeared (middle) and area that is new (bottom) for three different indicators - Tjan (left), Tjul (middle) and RR (right). The indicator values are ranked based on temperature (Tjan and Tjul) and precipitation (RR), with an indicator value 1 representing the species with the coldest/driest conditions and indicator value 8 representing the warmest/wettest species. Plots with significant differences between three or more indicators are outlined in black

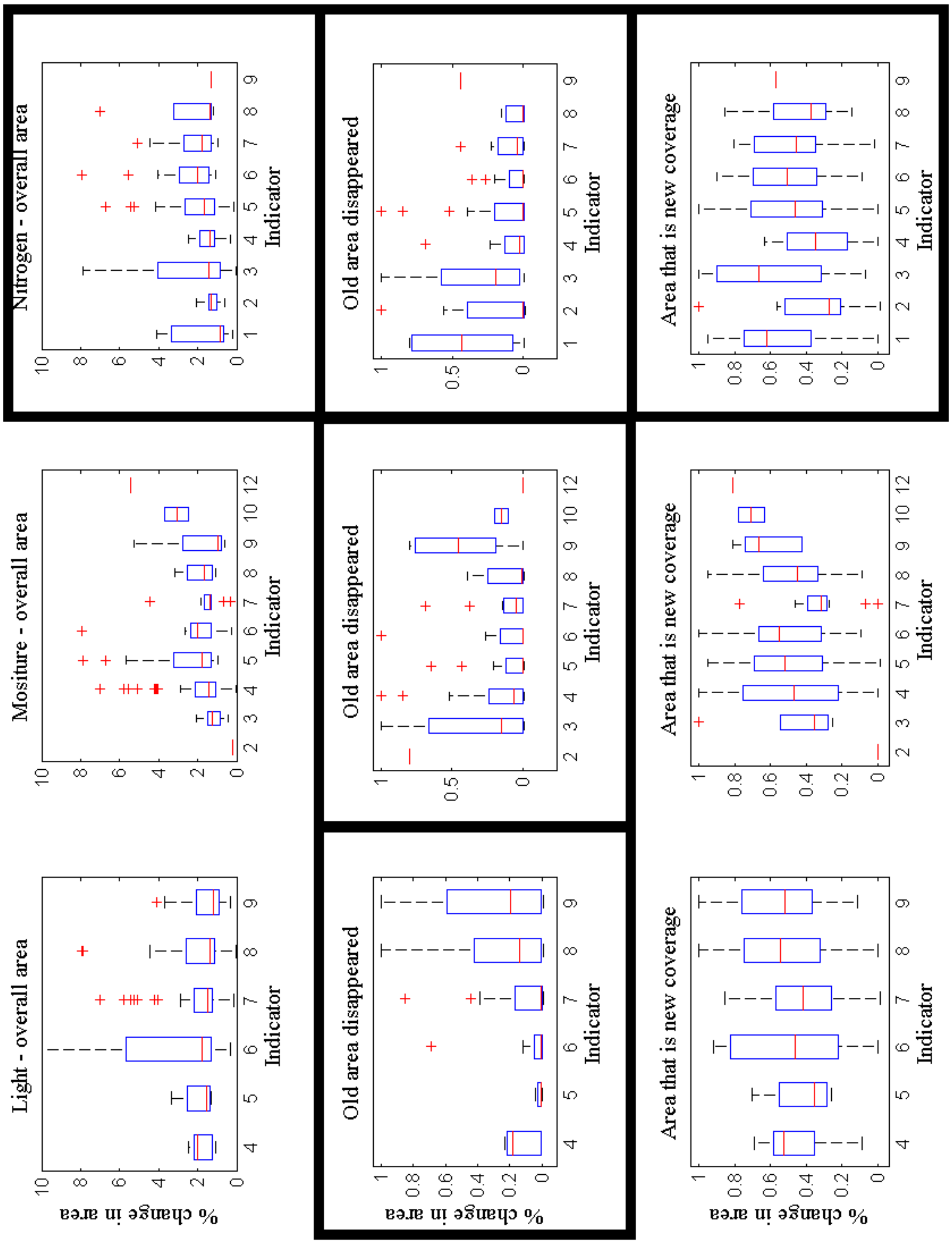

Figure 22 Percentage change in total area for L, M and N Ellenberg values. Plots with significant differences between three or more indicators are outlined in black

The wetter species increase more than the drier species (top middle Fig. 22), where species with M = 3 showed a significantly smaller increase than those with M=5 and 10. Species with M=1, 2, 11 and M=12 are infrequently observed, therefore no significant difference is obtained. Although species with M=7 had a significantly smaller proportion of new area (bottom centre Fig. 22). For the older species, those with M=4-6 had smaller decreases than those with M= 3 and 9 (centre Fig. 22). This suggests that the ‘moderately wetter’ species are expanding into more areas than the drier species, without losing previous coverage.

For light, the change in coverage was similar over most of the indictor values. The only significant differences came from the old area disappeared (left middle, Fig. 22). The group where L=6 and 7 have a significantly smaller decrease compared with species with L=8 or L=9. Overall, species with a higher L value showed the biggest decrease in old area coverage.

Significant differences exist on the nitrogen indicator values (right side, Fig. 22). For the overall percentage change in area, species with N=2 and N=4 had significantly smaller increases in coverage compared with those with values between 5 and 7. This was mainly caused by larger portions of older area being covered. Species where N=3 had a significantly larger decrease than those with values 4 to 8. For the percentage of area that has only been covered post 1900, there was no general trend. N=3 values were significantly higher than N=2 and N= 4.

5.5 Discussion and conclusion

We have framed the discussion against the two key aims of the paper: (a) can herbarium records be used to evaluate climatic effects on vegetation responses? And (b) is there a correlation between EV and EIV of key plant species and spatial patterns of change in their geographical distribution over this time period?

5.5.1 Aim (a)

The results show that it is possible to examine changes in plant species geographic distributions using historical records. Before now, historical records had been used to identify plant phenological changes (Fitter and Fitter 2002; Lavoie and Lachance 2006), to predict changes in species distribution or analyse patterns of l invasion of alien species (Loiselle et al. 2008; Crawford and Hoagland 2009). Our study shows that these records can be integrated into a spatial assessment of vegetation change across landscapes and used to understand potential drivers of that change. In this paper we focused on analysing trends where plants were seen to decrease in their distribution, however we also looked at increases in Red list species. One of the main criticisms of using historical plant records in scientific studies is that variation in collection methods could result in biased data. Besides analysing the increase in geographical distribution of plant species, analysis should be concentrated on the loss emphasizing that the plant species were present in the past but not present or decreasing at the present-day.

5.5.2 Aim (b)

In this study, species coverage showed significant differences in the Tjan EIV values, showing decrease in colder species. We showed that species sensitive to increased January temperatures were less abundant in the past. No significant differences were found for the Tjul EIV. Kosanic et al. (2014b) has shown positive trends in maximum and mean temperatures in West Cornwall.

We also found changes in species distributions based on RR and M values. EIV for RR and EV for M showed an increasing prevalence of moderately wetter species in the present although no positive trends in annual or seasonal precipitation are evident (Kosanic et al. 2014b). Trend detection in precipitation is difficult due to high variability and our results show that small changes in precipitation could influence species distribution. Few significant differences were found with the L for EV, which otherwise may have occurred with changes in species composition (Dzwonko 2001). Differences in the N indicators, with those associated with lower soil fertility show a larger loss of area coverage which could point to a more climate-driven effect. This suggests a decrease in range for those plant species that require high light and low nutrients (which suggests that they are being out-competed) and the ones that are most likely to have increased in range are those with high moisture requirements.

In conclusion we show how historical vegetation data can be used to track changes in the geographic distribution of vegetation and demonstrate that Ellenberg values can indicate environmental changes through time. We argue that further research should be conducted on microclimates and species distribution changes, providing a more firm link between EV/EIV values and climate change.

6. Vegetation change over West Cornwall (South West England) in response to climate change and importance of local conservation

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Author contributions:

A. Kosanic conceived and designed the experiments, formulated the research hypotheses (with guidance from KA and SH) and analysed the data. KA, SH, CHF and AK co-wrote the paper but the writing was led by AK with iterative comments and input from other authors.

6.1 Abstract

This study tracks vegetation change at the local scale over West Cornwall (South West England) which was divided into three distinct areas: an area to the North of the region (called “North Border Cells”), an area defined as the southern edge of the region (“South Border Cells”) and an area in the central part of the region (“Central West Cornwall Cells”). Analysis was conducted using historical (pre-1900) and recent vegetation records (post-1900), with a major focus on species lost from this region over that time period. For this purpose botanical records from a historical Flora published in 1909 (Davey’s “Flora of Cornwall”) and contemporary data available online were used. Both data sets were spatially analysed within a GIS, and species loss was detected for three distinct geographical areas within West Cornwall. Results showed that the loss was the highest in South Border Cells (11 species), compared to the loss from Central West Cornwall Cells (6 species) and North Border Cells (8 species). Results on a species decrease at the local scale were different to the results of another study of national research in “Change in British flora 1987-2004”. The different between result at national and local scales amplifies the importance of local scale conservation and research. The results of this paper show that two species (Mountain Melick *(Melica nutans)* and Filed Eryngo *(Eryngium campestare)*) were extinct from West Cornwall and decreased at the national scale.

6.2 Introduction

Recent climate change has led to changes in the geographical distribution and phenological responses of plant species and in some places, to species extinction (Hannah et al. 2002; Parmesan and Yohe 2003; Thomas et al. 2004; Thuiller et al. 2005a). It has been generally accepted that during the 20th and 21st century changes in plant species geographic distribution have followed two patterns: poleward movements and/or elevation shifts (Walther et al. 2002; Root et al. 2003; Parmesan 2006; Moritz and Agudo 2013). For example changes in the altitudinal range of 1-4 meters per decade have been detected for plant species in the European Alps (Grabherr et al. 1994) in response to climate, as well as changes in the altitude of tree lines associated with seasonal warming (Harsch et al. 2009). Furthermore, changes in latitudinal range have been observed for European forest herb species (Skov and Svenning 2004) as well as in woody plant species in the Arctic region (Crawford and Jeffree 2007) and plant species in the UK (Braithwaite et al. 2006). Some authors have identified that changes in geographical distribution result in an increase in the risk of extinction, as changes in distribution lead to habitat fragmentation and reduction in population size (Spielman et al. 2004; Dawson et al. 2011). It is likely that such changes will be even more pronounced given the climate change scenarios projected for the end of 21st century (Thomas et al. 2004; Parmesan 2006; Chen et al. 2011). Nevertheless, the magnitude of extinction risk will vary regionally and locally depending on the magnitude of climate change in the region but also on rate of land use change (e.g. habitat destruction and fragmentation). This will impact species individually, as some species will be less resilient to rapid climate change due to a lower range in their climatic envelope (i.e. climatic conditions in which species can persist) and therefore will become more vulnerable to the regional and local extinction (Thomas et al. 2004). There is still a need for an attribution method that could link range changes and extinction with climate change for most of the species at the local scale (Parmesan 2006). However, some studies shows that Ellenberg values, which define plant sensitivities to abiotic factors, can be used as an indicator of environmental change (Pignatti et al. 2001; Kosanic et al. 2014a), (Kosanic et al.2014a-in submission).

While national extent mapping is frequently used to identify species current distribution and conservation status (Preston et al. 2002; Braithwaite et al. 2006), it does not carry much useful information about patterns of local spatial-temporal changes in vegetation.

Local and regional scale research is important because it helps to understand species geographical changes and their current distribution patterns (e.g. extent of habitat fragmentation) as well as fine scale extinction rates (Foley et al. 2005). Furthermore, such research can identify the species that experience range changes or loss locally and can be important as a part of regional identity. Regional identity is defined as an important trait of a region (e.g. landscape, biodiversity, names of the places, historical monuments, dialects, local food), and it has been crucial to preserve local and regional landscape, for planning, marketing, conservation and to improve regional economic development (Paasi 2012). Change in species range and their loss at the local and regional scale leads to changes in ecosystem composition, and consequently can affect the delivery of ecosystem services (e.g. provisioning, regulating, cultural and supportive services) which are thought to be essential in supporting human wellbeing (MEA 2005; Rands et al. 2010; Beaumont et al. 2011). Ecosystem composition could be changed, with a loss of single ‘key species’ (species that play an important role in ecosystem composition) or even multiple species, but it is still unknown to what extent this can impact ecosystem functioning (Hooper et al. 2005; Lavergne et al. 2006; Bertrand et al. 2011). Therefore, another approach to management has been developed, placing the focus on species that have been identified throughout the literature as “key-species”, ‘identity species’ or “landscape species”, they could be crucial for the regional identity and ecosystem services (Mills et al. 1993; Simberloff 1998; Rates 2001; Gibbons and Boak 2002; Sanderson et al. 2002; Manning et al. 2006; Schaich et al. 2010; Natural England 2012). To do so, this study argues that conservation should not solely focus on threatened or rare species. The characteristics of common species do differ from those of rare species (Kunin and Gaston 1993), however, both are susceptible to population genetic response to habitat fragmentation (Honnay and Jacquemyn 2007). Instead of focusing on just rare and/or a common species (Gaston and Fuller 2008) at the local or regional scale, more is to be gained by improving our understanding about which species are vulnerable locally or regionally (Matthies et al. 2004). Therefore appropriate conservation strategies could be put in place to protect vulnerable plant species (McCarty 2001; Root et al. 2003; Thuiller et al. 2005b; Rands et al. 2010). This represents an important gap, given that analysing historical vegetation change at a local versus national scale is crucial for the appropriate management of vulnerable plant species and provides a baseline for better projections in the face of climate change (Beissinger and Westphal 1998; Thuiller et al. 2008).

The area on which this research is focused on is West Cornwall, a peninsula situated at south-west of England and it is a part of Cornwall County (Fig. 23). West Cornwall and its ‘regional identity’ is of particular importance to the United Kingdom given its outstanding natural beauty and diverse habitats (i.e. wetlands, headlands, woodlands) as well as its cultural and historical heritage (Cornish hedges, old mining sites, archaeological sites) and therefore provisioning with ecosystem services needs to be maintained. West Cornwall is suitable for this type of research as it has a good availability of historical and current vegetation records (Davey 1909; NBN 2013).

6.3 Aims

The aims of this study were three-fold. First, this study investigated changes in plant species distribution at the local scale. Second, we investigated whether changes in plant species distribution over the local scale were different to their changes at the national scale. The third aim sought to identify which plant species were lost from the region in the period since 1900. The gain of plant species post-1900 will not be analysed in this study due to possible difference in surveys (contemporary records were more systematically recorded, then historical ones), between historical and contemporary records. This study is aiming to provide an understanding of why preserving the vegetation at local and regional scales is important (at the example of West Cornwall) in the contemporary time-frame, when concepts of natural and static distributions are more unstable than ever, as many geographic distributions will show little overlap between current and future distributions (Thomas 2013). Protection of existing ecosystems will be far less expensive than losing them (Rands et al. 2010), because the loss of species at local and/or regional scale will result in the need to either ‘import’ or travel to ‘benefit’ from unique ecosystem services, which will be more costly than having them at hand.

6.4 Data and Methodology

This study analysed changes in local geographic distribution of vegetation over West Cornwall, (Fig. 23). Historical vegetation data (pre-1900) from “The Flora of Cornwall” (Davey 1909) and contemporary vegetation records (post-1900) were obtained from the “New Atlas of British and Irish Flora” (Kosanic et al. 2014a). Both data sets were used to investigate and map the past and present geographical distribution of plant species over west Cornwall. 381 plant species were searched for in “The Flora of Cornwall” (Davey 1909), and 1274 specimens (i.e. 123 plant species) were digitised using geo-referenced points into ArcGIS (Kosanic et al. 2014a). Historical records contain descriptions of species (genus and specific epithet) and localities where specimens were collected but these were uncertain, and this uncertainty was handled by a point radius method (Wieczorek et al. 2004; Guralnick et al. 2006), as described in Kosanic et al. (2014a). Contemporary records were imported from the NBN Gateway and also attributed to 10km grids cells in ArcGIS (NBN 2013), to analyse the changes in geographic distribution and loss between current and historical vegetation data.

1) Our first objective was to analyse changes in geographical distribution within the 10km grid cells over the study area (West Cornwall) (Fig. 23). To analyse changes in species geographic distribution and extinction locally the study site (West Cornwall) was divided into three areas: North Border Cells (NBC), Central West Cornwall Cells (CWCC) and South Border Cells (SBC), these terms will be used throughout this study (Fig. 23). To achieve this, attributed tables (past vs. present) for each 10 km grid cells within each particular area (i.e. North Border Cells) in ArcGIS, were cross-checked to detect ‘species loss’ and detect the loss at the local scale between historical and contemporary records. The species that were present in the past but absent in the present were defined as ‘loss species’ for each particular 10 km grid cell within these three areas. We also tracked which of these species were on the IUCN Red List and BAP (Biodiversity Action Plan-volume 4) list (Natural England 2012) in order to identify whether the loss within grid cells was related to those species that were most at risk or endangered.

2) Objective two was to compare changes in plant species geographic distribution at the local scale (West Cornwall) to changes in their distribution at the national scale (Braithwaite et al. 2006; Parmesan 2006). For this results from the first objective were used (i.e. species that are experiencing loss at the local scale) and compared to the results of a change at the national scale using research from *Change in the British Flora 1987-2004* (Braithwaite et al. 2006); which identified the changes by looking at (1) national range change in the individual species, (2) national range change in the species group and (3) national range change in the broad habitat (Braithwaite et al. 2006). Furthermore, Braithwaite et al. (2006) calculated the change by Change Factor (CF) and this for the national scale was calculated using a t-test with a significant decrease/increase if $p \leq 0.5$ or decrease/increase was marginally significant if $0.05 < p \leq 0.10$ (Table 11). More on this method was described in Braithwaite et al (2006).
3) To address objective 3 it was analysed which plant species were lost in the post-1900 period from the study area of West Cornwall and in order to achieve this we analysed all 24 grid cells to detect absence in post-1900 vegetation data. This was examined in a way to cross-check attribute tables of historical (pre-1900) and contemporary vegetation records (post-1900) in ArcGIS.

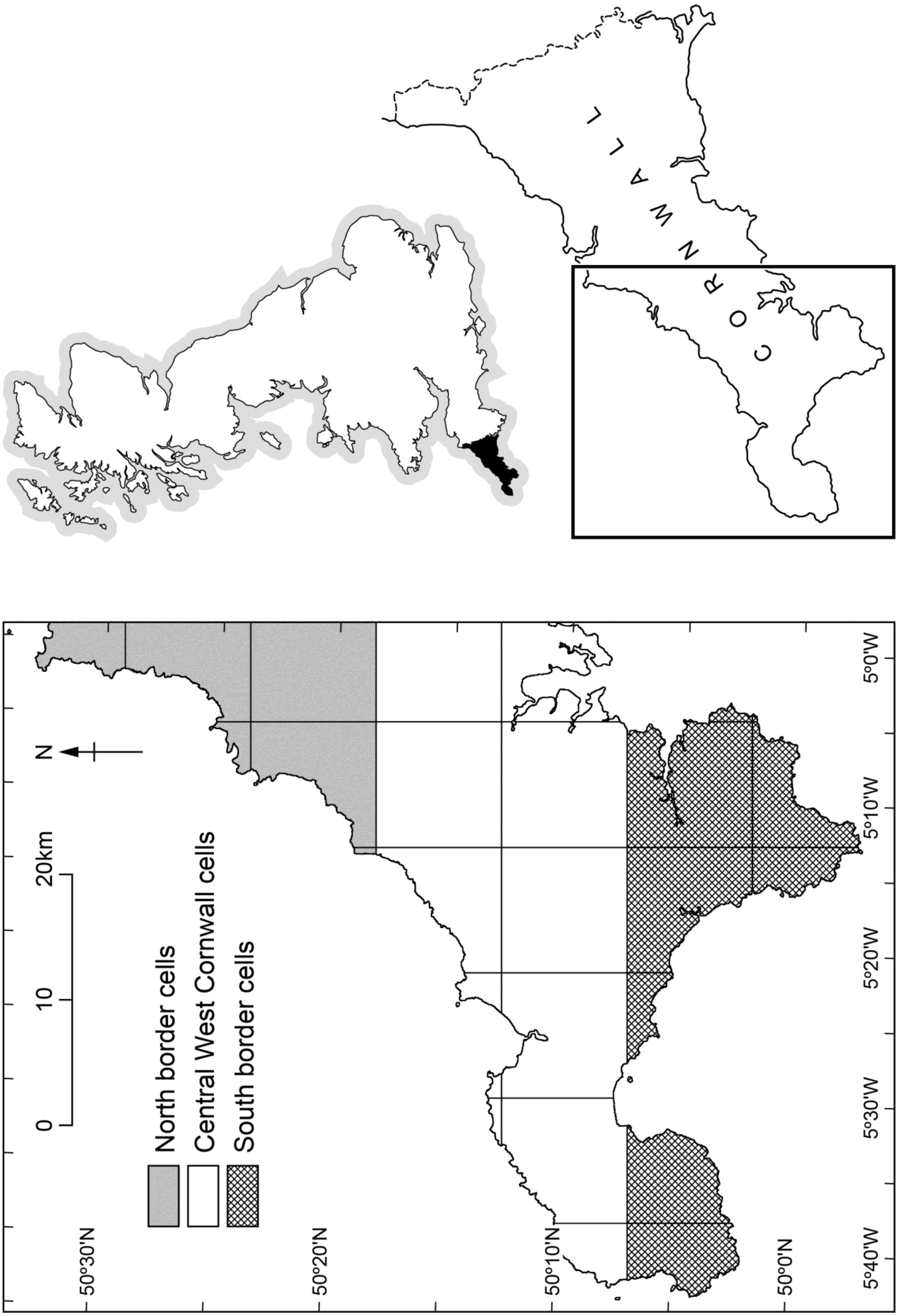

Figure 23 Study site of West Cornwall divided in three areas: North border cells, Central West Cornwall cells and South border cells

6.5 Results

6.5.1 Objective 1

In this study the loss of plant species was analysed within the NBC, CWCC and SBC. We found that 11 plant species had disappeared from the SBC, 6 species from the NBC and 8 species from the CWCC (Table 10). This first analysis showed a difference in the local geographic distribution of plant species, but more importantly showed that not only IUCN Red List species or BAP list species were lost locally. For example Field Eryngo (*Eryngium campestre*), was lost from the SBC of West Cornwall, which is important for a medical use and as a food plant for the Common Snail *(Helix Aspersa)* (Iglesias and Castillejo 1999; DBIF 2008). This species also belongs to the coastal grassland habitat, a priority habitat identified as a part of landscape character Cornwall's biodiversity action plan project (CBI 2011). Another example is the Rough Marsh Mallow (*Althaea hirsute*) which was lost at NBC of West Cornwall, important for medical purposes and a priority conservation habitat as a part of Cornwall's biodiversity action plan project (CBI 2011). Welted Thistle (*Carduus crispus*) is a common species important as a part of hedges and hedgerows habitat also known for its medical purposes (Zhang et al. 2002). *Carduus crispus* is important as a primary larval food plant of Painted Lady *(Vanessa cardui)* (DBIF 2008). It was lost from NBC and CWCC.

Table 10 Loss of plant species from 10 km grid cells in South Border Cells, Central West Cornwall Cells and South Border Cells. Those in bold/italic are lost species belonging to the IUCN Red List and those in bold are species belonging to the BAP list of species (JNCC 2010; IUCN 2014)

South cells-lat. and common name	Central cells-lat. and common name	North cells-lat. and common name
Alchemilla filicaulis subsp. Vestita/no common name	*Anagallis arvensis subsp.foemina/Blue Pimpernel*	*Althaea hirsute/Rough Marsh Mallow*
Clinopodium acinos /Basil Thyme	*Carduus crispus/Welted Thistle*	*Alchemilla filicaulis subsp. Vestita/ no common name*
Cystopteris fragilis	*Drosera anglica/ Great Sundew*	*Anagallis arvensis subsp.foemina/ Blue Pimpernel*
Drosera anglica/Great sundew	*Festuca arenaria/ Rush-leaved Fescue*	*Carduus crispus/ Welted Thistle*
Eryngium campestre/Filed Eryngo	*Legousia hybrid/ Venus's-looking-glass*	*Lavatera cretica/ Cornish Mallow*
Festuca arenaria/ Rush-leaved Fescue	*Melica nutans/ Mountain Melick*	*Medicago sativa subsp. falcata*
Legousia hybrida/ Venus's-looking-glass		*Melica nutans/Mountain Melick*
Lavatera cretica/Cornish Mallow		***Oenanthe pimpinelloides/Corky-fruited Water dropwort***
Lycopodium clavatum/ Stag`s-horn Clubmoss		
Medicago sativa subsp. Falcata/ Sickle medick		
Melica nutans/Mountain Melick		

6.5.2 Objective 2

It was found that 17 plant species were lost from different local sites in West Cornwall looking at pre- and post-1900 plant species distribution (Table 11). When comparing these results with change at the national scale from *Change in the British Flora 1987-2004* (Braithwaite et al. 2006), results showed a difference between in all three categories; individual species level, group level, habitat level (Table 11). For 8 species out of 17 (Table 11); a national scale comparison was not possible due to the lack of data analysis at the national scale (i.e. *Althaea hirsute*/Rough Marsh Mallow). For example, Basil Thyme (*Clinopodim acinos*), was lost from SBC of West Cornwall; also a decline was detected on the national scale (Table 11). Basil Thyme is good indicator of a threatened habitat, conversion of limestone and chalk pastures to arable land and is an important food for the larva of the moth Choleopora tricolor (DBIF 2008). Basil Thyme is also classified as of principle importance for conservation in West Cornwall and national scale (Table 11) (CBI 2011). Another example is the Great Sundew, (*Drosera anglica*) a part of bog habitat and the loss of species was detected locally and nationally, and on a habitat level which is also a priority habitat for conservation in West Cornwall (Table 11) (DBIF 2008). Species such as Rush-leaved Fescue (*Festuca arenaria*); a part of coastal habitats and an important host for invertebrates such as *Diptera*, *Lepidoptera*, experienced a decline on a local scale, also classified as a nationally scarce species. *Festuca arenaria* is important for conservation as extinction of this species can endanger butterflies and moths, such as *Danaus plexippus*, a rare migrant from North America, nationally scarce but with a particular concentration in Cornwall and Scilly Isles. Cornish Mallow (*Lavatera cretica*), is a host plant for *Apion malvae* nationally rare species but an important part of the Cornish landscape and therefore regional identity (DBIF 2008; CBI 2011; Frank et al. 2012). There were no data on changes for these species in *"Change in the British Flora 1987-2004"* (Braithwaite et al. 2006), however, as they are nationally scarce species it is important to conserve them locally as local extinction risk might turn into national extinction risk.

Table 11 Changes in plant species distribution at national scale for the 17 species that are disappearing from North Border Cells, Central West Cornwall Cells and South Border Cells of West Cornwall. Changes in species group and broad habitats are on national scale. BH1-Broadleaved, mixed and yew woodland; BH3-boundary and linear features; BH6-Neutral grassland; BH7-Calcareous grassland; BH10 -Dwarf shrub heath; BH11, 13 & 14-Wetland habitats; BH12-Bog; BH16-Inland Rock (Braithwaite et al. 2006; NBN 2013)

Plants name (absence from NBC,CWCC and SBC), *lat. and common name*	**National change individual species level**	**National change on a species group**	**National change on Broad habitats level**	**National importance for conservation**
Althaea hirsute/*Rough marsh-mallow*	*no data*	*no data*	*no data*	Protected plant (Schedule 8)
Alchemilla filicaulis subsp. Vestita/*no common name*	*no data*	*no data*	*no data*	Least concern
Anagallis arvensis subsp.foemina/*Blue Pimpernel*	*no data*	*no data*	*no data*	Least concern
Carduus crispus/Welted Thistle	*decrease*	*no change*	*BH3-increase not significant*	Least concern
Crepis biennis/*Rough Hawk's-beard*	*increase*	*increase not significant*	*BH6-no change*	Least concern
Clinopodium acinos/*Basil Thyme*	*sharp decline*	*significant increase*	*BH16-decrease marginally significant,* *BH1 - decrease marginally significant,*	Species of principle importance
Cystopteris fragilis/ *Brittle Bladder-fern*	*decrease*	*significant decrease*	*BH16-decrease marginally significant,* *BH1 - decrease marginally significant,*	Least concern
Dianthus armeria/ *Deptford pink*	*no data*	*no data*	*no data*	Species of principle importance
Drosera anglica/*Great sundew*	*decrease*	*no change increase not significant*	*BH11,13 and14-no change* *BH1- decrease marginally significant,*	Not threatened
Eryngium campestre/ *Field Eryngo*	*no data*	*no data*	*no data*	Critically endangered
Festuca arenaria / *Rush-leaved Fescue*	*no data*	*no data*	*no data*	Nationally scarce
Legousia hybrida/ *Venus's-looking-glass*	*decrease*	*increase not significant*	*BH3- increase not significant*	Scottish biodiversity list
Lavatera cretica */Cornish mallow*	*no data*	*no data*	*no data*	Nationally rare
Lycopodium clavatum/ *Stag`s-horn Clubmoss*	*increase*	*no change*	*BH10-significant decrease*	Species of principle importance
Medicago sativa subsp. Falcata/*Sickle medick*	*no data*	*no data*	*no data*	Nationally scarce
Melica nutans/*Mountain Melick*	*decline*	*significant decrease*	*BH1-, decrease marginally significant* *BH7-significant decrease, BH16-decrease marginally significant*	Least concern
Oenanthe pimpinelloides/ *Corky-fruited Water dropwort*	*increase*	*increase not significant*	*BH6-no change*	Least concern

6.5.3 Objective 3

The third objective was to investigate species that had become extinct from West Cornwall throughout the 20th and 21st centuries. Two species were found as present in historical records (pre-1900) but not in current vegetation data (post-1900). These species were Filed Eryngo *(Eryngium campestare),* and Mountain Melick *(Melica nutans)* and they are not part of the IUCN Red list and BAP list species. Also Mountain Melick *(Melica nutans)* is a host plant for moths *Elachista apicipunctella* and *Elachista gangabella*, and a part of priority conservation habitat at the local scale (DBIF 2008). Overall results showed the difference between losses of plant species in West Cornwall. Two species were lost from West Cornwall, 11 species were lost in SBC, NBC lost 8 species and for CWCC loss was detected for 6 species. These 'local differences' in species loss showed that species could be conserved locally and therefore kept locally and in the region of Cornwall.

6.5.4 Ellenberg and Environmental indicator values

Species that were lost from the range of West Cornwall had a broad range of environmental indicator values (EIV) (low or high January and June temperature) and Ellenberg values (EV) (showing species sensitivity to environmental change for L-light, M-moisture, N-nitrogen) (Hill et al. 2004). This indicates different microclimates around West Cornwall. For example, Mountain Melick *(Melica nutans*) has very low January EIV (1.9°C). The only pattern that was noticeable for the species that were lost from NBC, CWCC, and SBC is that they all had low to moderate N-Ellenberg values and high L values. Loss of species with low to moderate low nitrogen values may be connected with convection to agriculture land or less precipitation in a case of bog species such as *Drosera anglica*. Loss of species with high light-(L) requirements can be explained that such species were outcompeted by species with higher nitrogen-N values (Funk 2013).

6.6 Discussion

Changing climatic conditions in West Cornwall may be causing changes in plant species distributions – for example, the data presented here suggest that range reduction and range shifts are occurring. Many species could face an extinction given their inability to adapt quickly enough (Davis and Shaw 2001; Thomas et al. 2004; Jump and Peñuelas 2005). Previous research on changes in vegetation distribution in Cornwall showed that EIV and Ellenberg values can be used as environmental change indicators (Kosanic et al. 2014a). Species that are lost locally have lower N-nitrogen values and some have a lower EIV January temperature consistent with results from Kosanic et al. (2014a) which showed a decrease in species with a lower EIV January temperature and lower N value.

Results from this study showed differences in loss of plant species at (1) the local scale, (2) in local vs national area (3) West Cornwall as a whole. For example Sickle Medick (*Medicago sativa subsp. Falcate*), a nationally scarce species, was lost from SBC of West Cornwall and such small scale range reductions could lead to habitat fragmentation, creating isolated populations of smaller population size and lower genetic diversity due to the bottleneck effect (Coates 1992; Frankham 1995; Pullin 2002; Walther et al. 2002; Spielman et al. 2004). Furthermore, smaller, fragmented populations with a higher differentiation rate and lower dispersal abilities will have a lower level of genetic variation (Reed and Frankham 2003; Alsos et al. 2012). This can happen through genetic drift and inbreeding depression, resulting in reduced population fitness (Reed and Frankham 2003; O'Grady et al. 2006). Such populations have a reduced ability to adapt to environmental change (e.g. climate change), (Frankham 1995; Reed and Frankham 2003; Spielman et al. 2004). Sickle Medick (*Medicago sativa subsp. Falcata*), (Table 10) as well as other species, for which loss from SBC of West Cornwall was detected, can be identified as marginal populations of the United Kingdom. However, NBC of West Cornwall can be also identified as a marginal population if species present there are lost from SBC and CWCC (Vucetich and Waite 2003).

The centre periphery hypothesis argues that marginal populations are more vulnerable to extinction as they are genetically less diverse than central ones (Vucetich and Waite 2003). This is important because species in West Cornwall are marginal populations of those in United Kingdom and therefore might be at a higher extinction risk. However, some may argue that it is not important to locally protect them given that their presence in other regions ensures that they remain nationally present. This study disagrees with this view for the following two reasons discussed below. It was found that in some cases a change (decline) at the local scale was not identical to its change (e.g. increase) at the national scale in category of species group (i.e. *Clinopodium acinos*-Basil Thyme). In this scenario, while it is a shame species experience a loss locally; its future is secured given that its national range is extending. This may or may not be true depending on the extent of genetic diversity that is lost through local extinctions (Dawson et al. 2011; Alsos et al. 2012). There is evidence in the literature that genetic diversity is a priority for the protection of biodiversity (Frankham 1995; Reed and Frankham 2003; Spielman et al. 2004) and this may be even more so critical for species such as *Festuca arenaria* or *Lavatera cretica* (Table 11), which we found were declining locally and nationally listed as rare species. This study also showed that two species (Field Eryngo-*Eryngium campestare*, and Mountain Melick- *Melica nutans*) disappeared from West Cornwall post-1900 which are critically endangered nationally showing the importance of local conservation. It is believed that local conservation has an important role in the protection of biodiversity. First, local scale research on climate variability and vegetation loss is the best starting point to identify the location and presence of micro-refugia (Ashcroft et al. 2012; Kosanic et al. 2014b). Micro-refugia are important to biodiversity conservation as such refugia populations, which are characterised by microclimates, have been identified to play an important role in protecting species from climate variability and maintaining genetic diversity by minimising genetic isolation (Ashcroft et al. 2012). This is especially important nowadays when we still lack the research on genetic diversity through the species national and global ranges (Moritz and Agudo 2013). Furthermore, species Ellenberg values and environmental indicator values could be used to identify favourable micro-refugia (Kosanic et al. 2014a), but more research should take place towards identification of such areas.

Second, local species conservation will ensure that the cultural identity of a landscape, its regional identity and provisioning with the ecosystem services is preserved. There is still a big gap in our current knowledge about the role that each species plays within ecosystem services. This may be because current conservation strategies are mainly directed towards IUCN and BAP species, neglecting the conservation of other ‘vulnerable’ species but which may be critically important from ecosystem services perspective and as such should be adequately protected. For example, species such as Cornish Mallow (*Lavatera cretica*) is not IUCN or BAP listed species but is nonetheless a key feature of the Cornwall landscape, is part of the UK cultural identity and is an important medicinal species. Losing these species at the local or national scale would therefore negatively impact Cornwall as well as the United Kingdom cultural ecosystem services and its landscape (Natural England 2012; Miller et al. 2014). *Lycopodium clavatum* is another example which may not be listed under the IUCN Red List, but is one of the earliest terrestrial plants on the planet and important for medical use. It is regionally endangered due to pasture improvement and afforestation and nationally classified as a species of principle importance (Orhan et al. 2007).

6.7 Conclusion

This study demonstrated a need to consider local conservation strategies, using the example of West Cornwall for two reasons: (1) local loss can be different to the one at the national scale and therefore impact overall species genetic diversity (local-national-global) maximising the risk of extinction; (2) species disappeared locally, might be important as ‘key species’ and as a part of the cultural landscape and ‘regional identity’. At present, conservation strategies are mainly focused on IUCN/BAP species and other locally vulnerable species might be omitted. Currently, Red list of IUCN does not take into account genetic diversity and it is not certain that only species that are presently defined as ‘rare species’ are truly endangered (Alsos et al. 2012). Therefore more research on local scale genetic diversity is needed. Also, future research needs to be directed towards better identification of individual species and their role in ecosystem functioning, composition and evenness. This is because there is still a lack of knowledge about how biodiversity loss affects biochemical processes, and therefore sets of ecosystem services and interactions between them (Balvanera et al. 2013). Changes in vegetation will impact ecosystem services in West Cornwall (e.g. regulating, provisioning, cultural) and might affect the landscape character of Cornwall (MEA 2005; Schaich et al. 2010; Natural England 2012; Balvanera et al. 2013). However, it is still unknown to what extent changes in ecosystem composition and functioning affects ecosystem services (Balvanera et al. 2013). In order to minimise these uncertainties more local scale interdisciplinary research is needed linking biodiversity loss, ecosystem functioning and ecosystem services and regional identity (e.g. cultural landscape), using the same spatio-temporal scales (Schaich et al. 2010; Balvanera et al. 2013).

7. Discussion and conclusion

The aims of this thesis were three-fold. The first aim was to analyse climate variability on the local scale over West Cornwall, using historical and contemporary instrumental data. The second aim was to assess changes in vegetation distribution in West Cornwall using historical records (collection of herbarium data) from “The Flora of West Cornwall”(Davey 1909) and contemporary vegetation records from the National Biodiversity Network (NBN 2013). A part of the second aim was also to identify species loss at the local scale in order to detect vulnerable species. In addressing the second aim it was necessary to compare the loss of species at the local scale of West Cornwall to their change at the national scale in order to show why local conservation is important. The third aim was to understand the links between local climate variability and species distributional change. In this chapter all the results from this research will be summarised, discussed and brought to the conclusion of this PhD thesis.

7.1 Discussion

7.1.1 Climate variability in West Cornwall

In order to investigate climate variability in West Cornwall, it was essential to check whether historical weather data met homogeneity requirements, as unhomogenized data can show trends not related to climate change (Wijngaard et al. 2003; Costa and Soares 2009; Brunet and Jones 2011). The first objective (to analyse trends in maximum, minimum and average temperature, and precipitation for annual and seasonal scales) could then be addressed. The analysis of the data undertaken towards addressing the first objective detected positive trends in the 20th and 21st centuries for mean annual temperatures, maximum temperatures and minimum temperatures. Positive trends for the seasonal temperatures in the 20th and 21st centuries were detected for the mean summer, autumn and spring temperatures, whilst the highest positive trends were detected for maximum summer, maximum autumn and maximum spring temperatures (Table 4). The Helston data set was restricted only to the 19th century and showed one positive trend for the spring mean temperature. Negative trends were detected for the spring, summer and autumn minimum temperatures in the 20th and 21st centuries. For the 19th century, one station showed a negative trend in spring maximum temperature

(Table 4). The Trengwainton garden station showed the highest variability in seasonal temperatures within one station (more in Chapter 4). This showed that trends in temperature change were mainly consistent with the changes at the national scale, except that the positive trends were detected in spring/autumn and not just during the summer or winter seasons (Ishigami et al. 2007; Jenkins et al. 2008). Other regional studies across Europe showed the highest temperature increase in winter and summer seasons, whilst for the Alps an increase was detected however in autumn temperatures (Böhm et al. 2001; Büntgen et al. 2006; Haylock et al. 2008; Kundzewicz and Huang 2010). Such different results show the importance of using historical weather data (whenever available) and local scale research, as local climate varies spatially and temporally and this information is needed to understand how landscapes may respond to future change. In addition, there is still a lack of understanding of climate change impacts at the local and regional scale across Europe, and more knowledge will help to put appropriate policies in place and minimise socio-economic and biodiversity loses (Fischer and Schar 2010).

Analysis of precipitation change showed negative trends for the 20th and 21st centuries. (Table 4 & 5). Only one positive trend in precipitation change over West Cornwall was detected in the 19th century for Helston autumn rainfall (Table 4). These results were different to the ones at the national scale, which showed a positive precipitation trend for the winter season and negative trends in the summer season (Alexander and Jones 2000; Osborn et al. 2000a). Furthermore, the highest positive trends in precipitation were detected for west Scotland and northeast England where northern and eastern Scotland and Northern Ireland showed negative precipitation trends for the summer season (Alexander and Jones 2000). These negative precipitation trends over West Cornwall, could be linked to the fact that precipitation is regionally and locally highly variable (Maraun et al. 2009), but also to the negative correlation with NAO index which will be discussed in more detail in a following section. As precipitation is more spatially and temporarily variable, which has been confirmed by studies across Europe, local climate research is essential to understand the changes and to minimise the impact on society and ecosystems (Domonkos and Tar 2003; Hajat et al. 2005; Colombo et al. 2007; Gonzalez-Hidalgo et al. 2009; Kundzewicz et al. 2012).

The second objective was to examine whether there was a correlation between NAO indices and the average of annual and seasonal maximum/minimum/mean temperatures and the average of annual and seasonal precipitation. To address the second objective, weather records were correlated with both station based and PC NAO indices for all stations except Helston, as the NAO PC index was not calculated this far back in time. Therefore, the correlation for Helston was only tested with the station based NAO index. The largest positive correlation (higher values of *r*- correlation coefficient) between NAO indices and temperature were detected for winter and spring temperatures in Falmouth, Camborne, Culdrose and Trengwainton stations (more in Chapter 4, Table 6). This result was consistent with the positive mode of the NAO index and its impact on Northern European winter temperatures (Hurrell and Van Loon 1997; Hurrell et al. 2003). Previous studies have been mainly restricted to investigate the correlation between the NAO index and mean monthly temperatures, whereas this research showed that analysis of maximum and minimum temperatures should be undertaken, as results can differ (Trigo et al. 2004). Also correlation between maximum and minimum temperature and the NAO index can bring better understanding in vegetation response to climate variability (Trigo et al. 2002; Stenseth et al. 2003; Trigo et al. 2004). There was no positive correlation with winter precipitation and the NAO indices. This can be explained by the fact that the trends in precipitation were negative. However, it was surprising that positive correlation with precipitation was detected for autumn in Falmouth and for spring in Camborne, which could be explained by the fact that the largest values of the NAO index occur between November and April (Stenseth et al. 2003). Findings from Chapter 4, on temperature and precipitation correlation with the NAO index, showed that it is important to perform analysis of both NAO indices (station based and PC based) and this should be performed whenever possible due to the temporal restrictions of PC data (Hurrell 2012).

The third objective was to investigate extreme precipitation events for stations with daily data. To address this objective return period analysis was performed for Camborne and Trengwainton garden stations; Culdrose station was excluded from this as the data set was too short. The results from the return period analysis showed that high intensity events (e.g. 50mm) were more frequent in the pre-1975 period (more in Chapter 4). This is consistent with the results from Rodda et al.(2010) that detected a decrease of high intensity precipitation events in the UK. Yet, these results of return period analysis are contrary to predicted trends for the end of the 20th and beginning of the 21st century, which estimated a higher intensity and frequency of daily extreme precipitation events (Osborn et al. 2000a; Maraun et al. 2009; Lloyd's 2010). Hence, contrary results confirm a high temporal and spatial variability of precipitation (Easterling et al. 2000a).

This PhD research showed that climate change research at the local scale is important to understand local climate variability, but also allows to better understanding of biodiversity response to climate change. Furthermore, climate change research on a local scale can be a good base for developing further projections but also for future analysis of Cornwall’s regional rate and pattern of climate change and the rate and pattern of land use change in response to climate change (Ordonez et al. 2014). For example, this is important as it has been known that if the rate of climate change is slow and the rate of land use change is slow, species will have more time to persist in a local environment or move to a nearby, favourable microclimate (Ordonez et al. 2014). In that way, it is possible to minimize local extinction and to keep species in Cornwall (Thomas et al. 2004). The findings from Chapter 4 suggested the importance of available historical weather records in understanding climate variability and climate change at the local scale, and improve the ability to predict future changes (Brunet and Jones 2011). The limitations of using historical weather data are that non-digitised historical records require digitisation, which is very time consuming, and the homogenization requirements of such data sets (Changnon and Kunkel 2006; Brunet and Jones 2011; Chandler et al. 2012).

7.1.2 Vegetation distribution change in West Cornwall

The second aim of this research was to understand vegetation change in West Cornwall. The fourth objective, as a part of this second aim, was to analyse whether historical vegetation records collected in “Flora of Cornwall” (Davey 1909), can be used to track changes in geographical distribution of plant species and detect their loss at the range of West Cornwall. This has been proven to be possible (Fig. 19); however as it was suggested in previous studies there are several limitations in using historical vegetation records and these issues were further highlighted by this research. Key challenges included the process of manual geo-referencing, taxonomical inaccuracy, estimation of uncertainty buffers and bias in data collections (i.e. current vegetation surveys are much more systematic) and these limitations needs to be addressed prior to analysis (Crawford and Hoagland 2009; Feeley 2012; Lavoie 2013). In Chapter 5 these uncertainties were tackled and discussed. In this study, the processes of geo-referencing and the calculation of uncertainty buffers were done manually. This required considerable work and time, but proved to be successful, even in the absence of automated geo-referencing programs which were developed for some countries (Lister 2011). Nevertheless, despite these limitations, the importance of historical data has been recognised by the scientific community, and making these data available in a digitised form is one of the major goals in biodiversity research today. Tracking the changes in species distribution, and understanding previous patterns of vegetation change might help in predicting future patterns and develop appropriate conservation strategies in Cornwall or anywhere locally and regionally, where such research is possible (Graham et al. 2004; Crawford and Hoagland 2009; Lister 2011; Feeley 2012).

The fifth objective was to investigate changes in geographic distribution of vegetation and vegetation loss over their range in West Cornwall using historical and contemporary vegetation records. Results from this objective were presented in Chapter 5. Changes in the geographical distribution of vegetation were analysed and showed the change at the overall range of species in West Cornwall (Table 7). Results for changes in the geographic distribution of plant species showed that a decrease in spatial distribution was detected for 18 species, and the decrease was larger than 50% in the case of 6 species. No change in geographic distribution was detected for 10 species (more in Chapter 5). This research also showed that when dealing with historical vegetation data vs contemporary data, changes in geographical distribution of vegetation should be mainly concentrated on species ‘loss’ and not ‘gain’ due to the fact that current vegetation surveys are more extensive than in the past (Elith et al. 2006; Elith and Leathwick 2007; Lavoie et al. 2007). However, some endangered Red list and BAP species experienced an increase and not just a decrease in West Cornwall (Table 8) (discussed in Chapter 5) (Braithwaite et al. 2006; IUCN 2014). Results from Chapter 5, also showed that the change for some species at the local scale was different to the change at the national scale (Table 8) and this showed the importance of local conservation strategies, which has been addressed by sixth objective in Chapter 6.

The sixth objective was to investigate the loss of species at the local scale within West Cornwall. The results showed a loss of species over all local areas of West Cornwall (North Border Cells, Central West Cornwall Cells and South Border Cells) (Fig. 23), with the highest loss detected in South Border Cells (Table 10). This result might be expected as the area of South Border Cells is the most southerly marginal population of the United Kingdom, and marginal populations are known to be less genetically diverse and more prone to extinction (Vucetich and Waite 2003). However, if the South Border Cells of West Cornwall was representing the area of current marginal populations, any further consequent loss of species will create a future ‘new’ marginal population area (i.e. West Cornwall Cells and North Border cells) which will be less genetically diverse and more prone to extinction. Loss at the local scale can lead to smaller isolated populations and habitat fragmentation causing lower genetic diversity within species population (Reed and Frankham 2003; Lienert and Fischer 2004; Spielman et al. 2004; O’Grady et al. 2006; Aguilar et al. 2008), impacting species existence on a local, regional and national scale.

Findings from Chapter 6, also showed that a loss of species at the local scale can be different to their change at the national scale, not just at individual species level, but also in species groups and habitats (Table 11), (Braithwaite et al. 2006), (discussed in Chapter 6). Another important result from Chapter 6, was that species which experienced the loss over different local areas (i.e. North Border Cells, Central West Cornwall Cells and South Border Cells), were not only ICUN Red list and BAP species (Table 10), and the main focus of current conservation strategies is on ICUN Red list and BAP species (IUCN 2008; CBI 2011). Furthermore, two species were found to be lost from the area of West Cornwall post-1900 (more in Chapter 6). These results amplify the importance of local scale research and identification of all species which were lost locally, to minimise future potential losses on the regional and national scale (Lienert et al. 2002; Matthies et al. 2004; McKay et al. 2005; Walker and Preston 2006). In addition, not only ICUN Red list or BAP species are endangered but also ‘common species’ could be vulnerable locally, and such species can be an important part of ecosystem functioning and therefore ecosystem services, contributing to the cultural landscape and regional identity of West Cornwall and therefore those species also need to be included in conservation scheme (Sanderson et al. 2002; Garibaldi and Turner 2003; Worm et al. 2006; Bowen 2010; CBI 2011; Paasi 2012; Martinez-Harms et al. 2015; Valls et al. 2015).

7.1.3 Linking local climate variability to vegetation change

The third aim was to understand the links between local climate variability and species distribution change. Objective seven was to investigate whether Ellenberg indicator values (EV= L-light, M- moisture and N-nitrogen) and environmental indicator values (EIV= Tjan-January temperature, Tjul-July temperature and RR-precipitation) can be used as a proxy for abiotic environmental change, and therefore, a link for climate change detection.

Correlation between changes in the geographic distribution of plant species, the area of coverage (pre-1900 and post-1900) and EV/EIV, showed an increase in the area (i.e. the area that was not recorded pre-1900, but recorded in a current records), for the species with a warmer January temperature (EIV- Tjan) (Fig. 21). Furthermore, the species with extreme environmental indicator values for precipitation (RR=1, 2 and 8) (Fig. 21), had a significantly greater loss in area (i.e. the area that was occupied pre-1900 but unrecorded in current records) than those with RR= 6. However, moderately wetter species with M= 4-6, showed an increase in new areas (i.e. the area that was not recorded pre-1900, but for which recent records exist), (Fig. 22). This could suggest that species loss was greater for habitat specialist species (i.e. species with low/high water requirements (Stohlgren et al. 2005; Evangelista et al. 2008). Ellenberg values for light (L) showed that species with higher values had the largest decrease in an old area (i.e. the area that was occupied pre-1900 but not currently present) (Fig. 22). A species with low Ellenberg value for nitrogen (N=1-3) showed significant loss) (Fig. 22), and this could suggest that species with higher light requirements and low nitrogen were outcompeted by high productivity species, which can impact changes in ecosystem composition (Bobbink et al. 2010; Tao and Hunter 2012) (more in Chapter 5).

These results showed that Ellenberg values and environmental indicator values can be used as a proxy for environmental change. Weather they could be used as a link between vegetation and climate change is still problematic as some results, such as temperature, precipitation and moisture indicator values, showed high to moderate consistency with a previous analysis from Chapter 4 (i.e. positive trends in annual and seasonal temperatures over West Cornwall). Nevertheless, to confirm this, more studies analysing the trends in microclimate and vegetation response need to be undertaken.

7.2 Conclusion

This PhD research showed the importance of using local historical weather records to allow the tracking of centennial climate change. The research has contributed new findings to the science of regional and local climatic change studies, and provides data that can help to understand and explain future change by incorporating historical data into climate models as a test of their utility. Digitising historical data is a challenging task, however, local data analysis gives enhanced knowledge and more understanding of local and regional climate change. Beside digitisation of data, it is also important to assess the nature and scale of data uncertainties; this would include quality checks of the data sets and make homogenization adjustments if needed. Beside the incorporation of historic data to test climate models, these data sets can help to understand the relationship with local and regional teleconnections (e.g. NAO index); allowing comparison with the relationship at the national and continental scales. Furthermore changes in intensity and frequency of extreme events, produces the most locally direct and the most costly impact on society and nature (Beniston et al. 2007; Rodda et al. 2010; Warren et al. 2014). Hence, an understanding of extreme events variability from local to regional scales over Cornwall can improve policy making and adaptation to extreme climate events.

This study was used to determine if historical vegetation data can be used to track changes in the geographic distribution of plant species and whether Ellenberg values and environmental indicator values could be used as an environmental change indicator and therefore provide an essential link which could relate these changes to local climate variability (Parmesan 2006; Parmesan et al. 2011).

Geo-referencing historical vegetation data from a paper format (i.e. collection of herbarium record) or herbarium records was an even more challenging and more time consuming task then digitising the weather data, as spatial uncertainties depend on the quality and accuracy of historical vegetation records. Spatial uncertainties in historical vegetation records could be addressed by using automatic geo-referencing programs, where spatial uncertainty buffers are already incorporated in the program, however this study showed that manual geo-referencing process is feasible, however is a task on its own. Uncertainty buffers are essential when dealing with herbarium collections, as they minimise spatial bias and allow the detection of changes in species geographic distributions as accurately as possible. This research showed that EV and EIV values can be used as an environmental indicator of vegetation change; however more local studies on microclimates are needed, as this could provide substantial evidence towards developing climate change attribution schemes. Local studies could identify whether vegetation distribution is affected by climate change or land use change. There has not been any systematic research on the magnitude and direction of land use change over West Cornwall, therefore it cannot be concluded that the changes in vegetation are only climate driven. Certainly, there has been land use change during present and past centuries throughout West Cornwall, but to what extent and in what speed of land use change vs climate change is unknown. This is an important point for future research in Cornwall, particularly as Ordonez et al. (2014), showed that the rate and pattern of climate change and land use change can vary locally and regionally.

Changes in vegetation distribution can vary if the comparison is made between the local and national scales. Furthermore, the results can also be influenced if comparison is made at different spatial levels (i.e. individual species level, species groups or habitats). This is important as it gives a much broader perspective on possible micro-refugia at the local and national scales and this gives an opportunity to prevent local extinctions (Dawson et al. 2011; Scherrer and Körner 2011). To fully understand to what extent changes in the geographic distribution of plant species, and their loss locally and regionally, will impact the genetic diversity and overall genetic pool of species, more genetic research is needed. Even with an acknowledgment of the fact that current lists such as IUCN Red List and BAP lists are the best starting point and a tool for current conservation strategies, it has to be kept in mind that those lists do not take into account the genetic diversity of the species (Dawson et al. 2011; Alsos et al. 2012). Therefore, they prioritise currently ‘endangered’ species where ‘common’ but potentially locally vulnerable species could be endangered and prone to extinction by the end of the 21st century, as is demonstrated as part of this PhD research. Protection of such species is very important as they contribute to local ecosystem functioning, regional identity, ecosystem services and as a result to the economic value of West Cornwall and Cornwall as a region (MEA 2005; Schaich et al. 2010; Paasi 2012; de Oliveira and Berkes 2014; Plieninger et al. 2015).

8. References

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