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Discussion

Reconciling climate action with the need for biodiversity protection, restoration and rehabilitation

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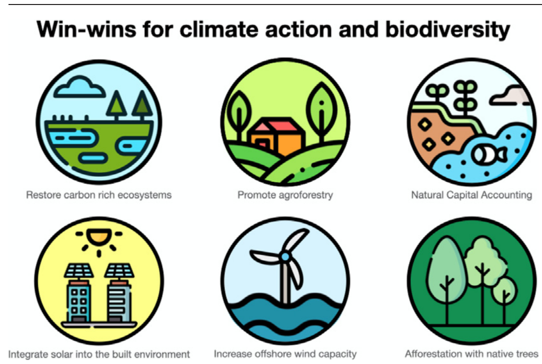
HIGHLIGHTS

- Climate change, biodiversity loss, and human activity are interconnected.
- Biodiversity considerations should be integrated into climate change actions.
- There are win-win strategies for climate mitigation and biodiversity conservation.
- Climate mitigation should be implemented in a "Right Action, Right Place" framework.

GRAPHICAL ABSTRACT



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ABSTRACT

Globally, we are faced with a climate crisis that requires urgent transition to a low-carbon economy. Simultaneously, the biodiversity crisis demands equally urgent action to prevent further species loss and promote restoration and rehabilitation of ecosystems. Climate action itself must prevent further pressures on biodiversity and options for synergistic gains for both climate and biodiversity change mitigation and adaptation need to be explored and implemented. Here, we review the key potential impacts of climate mitigation measures in energy and land-use on biodiversity, including the development of renewable energy such as offshore and onshore wind, solar, and bioenergy. We also assess the potential impacts of climate action driven afforestation and native habitat rehabilitation and restoration. We apply our findings to Ireland as a unique case-study as the government develops a coordinated response to climate and biodiversity change through declaration of a joint climate and biodiversity emergency and inclusion of biodiversity in key climate change legislation and the national Climate Action Plan. However, acknowledgement of these intertwined crises is only a first step; implementation of synergistic solutions requires careful planning. We demonstrate how synergy between climate and biodiversity action can be gained through explicit consideration of the effects of climate change mitigation strategies, such as energy infrastructure development and land-use change, on biodiversity. We identify several potential "win-win" strategies for both climate mitigation and biodiversity conservation. For Ireland, these include increasing offshore wind capacity, rehabilitating natural areas surrounding onshore wind turbines, and limiting the development of solar photovoltaics to the built environment. Ultimately, climate mitigation should be implemented in a "Right Action, Right Place" framework to maximise positive biodiversity benefits. This review provides one of the first examples of how national climate actions can be implemented in a biodiversity-conscious way to initiate discussion about synergistic solutions for both climate and biodiversity.

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1. Introduction

Globally, we are facing simultaneous climate change and biodiversity crises (IPBES, 2021; IPCC, 2021). Despite this being a worldwide problem, mitigation measures will largely be implemented at national and local scales. Governments recognise that both the climate and biodiversity crises threaten life support systems, livelihoods, and quality of life for people through their direct and indirect impacts on provisioning (food, shelter) and regulating (climate, nutrients, pollination) ecosystem services (Dasgupta, 2021), as well as threats to cultural services (spiritual, aesthetic, relational) (Chapin et al., 2000; Díaz et al., 2006; Jones et al., 2019). The biodiversity and climate crises are entwined in a complex system of feedbacks, with biodiversity part of the Earth system regulating climate, and climate in turn determining biodiversity patterns and trajectories. There is increasing awareness that climate change and biodiversity loss cannot be treated as independent issues (e.g., Zarnetske et al., 2021). For example, the United Nations Sustainable Development Goals (SDGs) directly include combating climate change and halting biodiversity loss, and climate and biodiversity also underpin the other SDGs (United Nations General Assembly, 2015). Accordingly, global consortia such as the InterAcademy Partnership (IAP), continue to work towards synthesising evidence-based solutions to these challenges (InterAcademy Partnership, 2021).

As we move to act urgently on climate change, we need to prevent further pressure on biodiversity and implement options that provide synergistic gains for mitigating both the climate and biodiversity crises. While mitigating climate change via reductions in greenhouse gas emissions generally benefits biodiversity at a global scale (Ohashi et al., 2019), these measures will largely be driven by national scale policies and initiatives. Therefore, it is important that individual governments incorporate biodiversity into their response to climate change. The Republic of Ireland (hereafter Ireland) is developing a synchronised national response to climate change and biodiversity loss by declaring a Climate and Biodiversity emergency and including biodiversity in climate legislation (Houses of the Oireachtas, 2021) and the government Climate Action Plan (Government of Ireland, 2021) in addition to the National Biodiversity Action Plan (NPWS, 2017) and the Biodiversity Climate Change Sectoral Adaptation Plan (Department of Culture, Heritage and the Gaeltacht, 2019). However, recognising that climate and biodiversity change require a coordinated response is only a first step. Implementing synergistic actions requires careful planning to prevent further biodiversity loss and identify and capitalise on opportunities that simultaneously mitigate both the climate and biodiversity crises (i.e., win-wins).

Here, we use Ireland as a case-study to explore and identify synergistic mitigation measures to both the climate and biodiversity crises. We first discuss climate action policy, planned climate actions and the utility of a natural capital accounting approach for planning and monitoring climate actions (Sections 1.1, 1.2). We then address the potential impacts of renewable energy development and land-use change on biodiversity and the biodiversity impacts of all life-stages of renewable energy generation for each of offshore wind (Section 2.1), onshore wind (Section 2.2), solar (Section 2.3), and bioenergy (Section 2.4). In addition, we discuss the potential of afforestation and native habitat rehabilitation and restoration as nature-based solutions for mitigating climate change and biodiversity loss (Sections 3.1, 3.3). This case-study provides a general framework for how climate actions can be implemented in a biodiversity-conscious way and intends to provoke discussion on developing synergistic solutions for the climate and biodiversity crises in other regions.

1.1. Biodiversity and climate goals in Ireland

In May 2019, Dáil Éireann (i.e., the House of Representatives of the Legislature of Ireland) became the 2nd country worldwide to declare a climate and biodiversity emergency (Dáil Éireann, 2019). The status of biodiversity in protected areas, seas and the wider countryside is generally in poor condition and continues to decline (NPWS, 2019, 2017). Climate change is negatively impacting Irish habitats, especially in coastal and upland environments (Gleeson et al., 2013). Expected increases in temperature, changes in precipitation patterns, weather extremes (storms and flooding, sea surges, flash floods) and sea-level rise will affect the abundance and distribution of Irish species. These pressures and threats are likely to increase over the next decade unless substantial action is taken (NPWS, 2017).

Ireland has recognized the importance of conserving biodiversity and has made commitments to increase the protection of species and their natural habitats.[1] The National Biodiversity Action Plan (2017–2021 - currently being renewed) sets out priority actions (NPWS, 2017). The Biodiversity Climate Change Sectoral Adaptation Plan (Department of Culture, Heritage and the Gaeltacht, 2019) recognizes the need to protect biodiversity from climate change as well as considering biodiversity as an adaptation tool for other sectors, with the potential for multiple co-benefits including water regulation and purification and carbon sequestration. It is therefore critical that the economy is decarbonised in ways that support established biodiversity ambitions and obligations.

The recognition for urgent climate action has led to policy actions such as Ireland's participation in the Paris Agreement on Climate Change (UNFCCC, 2015) and legislating for the national 2050 climate objective "to pursue and achieve no later than 2050, the transition to a climate resilient, biodiversity-rich, environmentally-sustainable and climate-neutral economy" (Houses of the Oireachtas, 2021). To meet decarbonisation goals, Ireland has developed a Climate Action Plan (Government of Ireland, 2021), to achieve a net zero carbon energy systems objective by 2050. Specific actions include increasing the amount of electricity generated from renewable sources from 30 % to 80 % by 2030, establishing 8000 ha of newly planted trees (i.e., afforestation) per year, and funding the restoration and rehabilitation of peatlands (Government of Ireland, 2021).

1.2. Natural capital accounting and nature-based solutions

Biodiversity provides ecosystem services and numerous resources for human well-being. For example, wetlands provide water purification, sediment retention, habitat for species as well as cultural enjoyment, and these services should be accounted for (Barbier, 2011; Farrell et al., 2021b). An emerging approach is to think of biodiversity as an asset (part of our natural capital) that needs to be maintained and managed to ensure the sustainable flow of resources and services it provides (Ekins et al., 2003; Mace et al., 2015; Maseyk et al., 2017). Natural Capital Accounting comprises systematic methods to measure and report on stocks (biodiversity, soils, water, geology) and flows (ecosystem services and benefits) of natural capital (Farrell et al., 2022; Maseyk et al., 2017). This quantification and systematization of the value of ecosystems, including the extent and condition of stocks of assets and flows of services and benefits, and tracking these changes over time, can assist in making decisions that benefit the environment, society, and the economy (Farrell et al., 2021a; Hein et al., 2020). Given that the location, quantity, and quality of natural capital stocks (including biodiversity) underpin greenhouse gas regulation in the atmosphere, natural capital accounting methods are strongly recommended for assessment and planning of flows of not only climate regulation services, but a range of interlinked services provided by natural capital.

Current practices for natural resource exploitation are inefficient and unsustainable not only in Ireland, but globally (Dasgupta, 2021). While economic benefits in the short term may be maximized, longer-term economic growth is hindered by unsustainable methods and their negative impacts on natural capital. By explicitly considering natural capital as underpinning economic activity and wellbeing, sustainable Nature-based Solutions can be developed to restore and rehabilitate degraded ecosystems to leverage natural assets for multiple climate and biodiversity related benefits (Keesstra et al., 2018; Maes et al., 2020; White et al., 2021). Throughout

[1] (EU Birds [Directive 2009/147/EC] and Habitats Directives (which provide for the Natura 2000 (N2000) network of protected areas), Marine Strategy Framework Directive (MSFD), EU Water Framework Directive (WFD), and EU Biodiversity Strategy (EC, 1992; EC, 2000; EC, 2008 and EC, 2009)).

this review, and in the context of climate mitigation action, we identify Nature-based Solutions that would be potential win-wins for biodiversity and climate in Ireland. While each country will have its own unique set of challenges and considerations, Natural Capital Accounting and the application of sustainable Nature-based Solutions can serve as general tools for synergistic climate and biodiversity loss mitigation.

While Ireland currently lacks detailed comprehensive land-use maps, we estimate current land-use using information available for specific sectors, and through resources such as the CORINE land cover database (European Environment Agency, 2018) (Fig. 1). Agriculture dominates land use in Ireland, with between 56 % (European Environment Agency, 2018) and 58.4 % (Central Statistics Office Ireland, 2020) of total land area dedicated to pasture and a further 11 % to non-pasture agriculture (European Environment Agency, 2018). A high proportion (over 12 %) of the land is classified as peat wetlands (European Environment Agency, 2018), but due to harvesting, drainage and overgrazing only a fraction of these peatlands can be considered functioning ecosystems (Department of Heritage, Culture and the Gaeltacht, 2017). While Ireland's dominant climatic biome is Temperate Deciduous Woodland (Ramankutty and Foley, 1999), and pre-historically 80 % of Ireland's land area was covered by trees (Mitchell, 1994), current tree cover is estimated at between 11 % (Department of Agriculture, Food and the Marine, 2017) and 9 % (European Environment Agency, 2018). Approximately half of current tree cover is plantation forest comprised mainly of non-native conifer species.

2. Development and expansion of renewable energy infrastructure

Ensuring access to affordable, reliable, sustainable and modern energy for all is one of the United Nations SDG's (United Nations General Assembly, 2015). The development and expansion of renewable energy infrastructure will happen within four sectors: offshore wind, onshore wind, solar, and bioenergy. There are three primary life stages of renewable energy facilities: construction, operation, and decommissioning. We outline the main biodiversity impacts identified for each stage within these four renewable energy sectors (Fig. 2) and discuss potential biodiversity mitigation methods. We also make recommendations for the implementation of each renewable energy source and life cycle stage (Table 1), and we identify potential opportunities for biodiversity protection and restoration within each sector.

2.1. Offshore wind farms

Offshore wind is still in early stages of development in Ireland. However, there is a Climate Action Plan target of 5 GW of offshore renewable energy by 2030. Currently, there are seven planned offshore wind projects that combined have the capacity to produce up to 3.8 GW of offshore wind energy. Together these projects plan to add around 260 wind turbines to the Irish Sea and 20 turbines to the Atlantic Ocean. The total size of the developments amount to around 434 km^2 in the Irish Sea, and about 4 km^2 in the Atlantic Ocean. Despite this relatively small footprint, there are potential impacts on biodiversity.

2.1.1. Constructing offshore wind farms

The installation of new wind turbines often leads to the destruction and/or alteration of the seabed, which negatively impacts species living on the seabed (Gill, 2005). Boulders are removed and the seabed is dredged to level it prior to installation and to provide trenching for cables that connect turbines to onshore substations. In the short-term, dredging increases turbidity which can negatively impact sedentary species (Gill, 2005). In the long-term, these construction activities can compact the seabed and alter its morphology. There are potential negative effects of pile driving in key spawning grounds, both from the perspective of fish stocks of interest to humans, and through trophic (food-web) effects on sea birds and other marine organisms (Perrow et al., 2011).

Negative impacts of offshore wind farm construction are, however, generally considered to be minor by most European Environmental Impact Assessment (EIA) reports (Vaissière et al., 2014), as the land needed for construction of wind turbines is considered negligible compared to the total area of the seabed. Additionally, evidence from previous EIA reports show that the seabed is recolonized by animals, algae, and plants relatively rapidly after construction is completed (Leonhard and Pedersen, 2006; Lindeboom et al., 2011; Vaissière et al., 2014). Technology is currently being developed for floating wind farms, in which turbines are placed on floating platforms (e.g., Hywind Scotland Wind Farm; https://www.equinor.com/). Future plans for offshore wind farm construction could employ floating wind farm technology to minimise negative impacts to the seabed.

Construction noise has been shown to negatively impact marine mammals (Madsen et al., 2006). Noise emissions from activities such as pile driving are sufficiently loud that they could cause temporary or permanent hearing loss in animals like the Harbour Porpoise, (*Phocoena phocoena*)

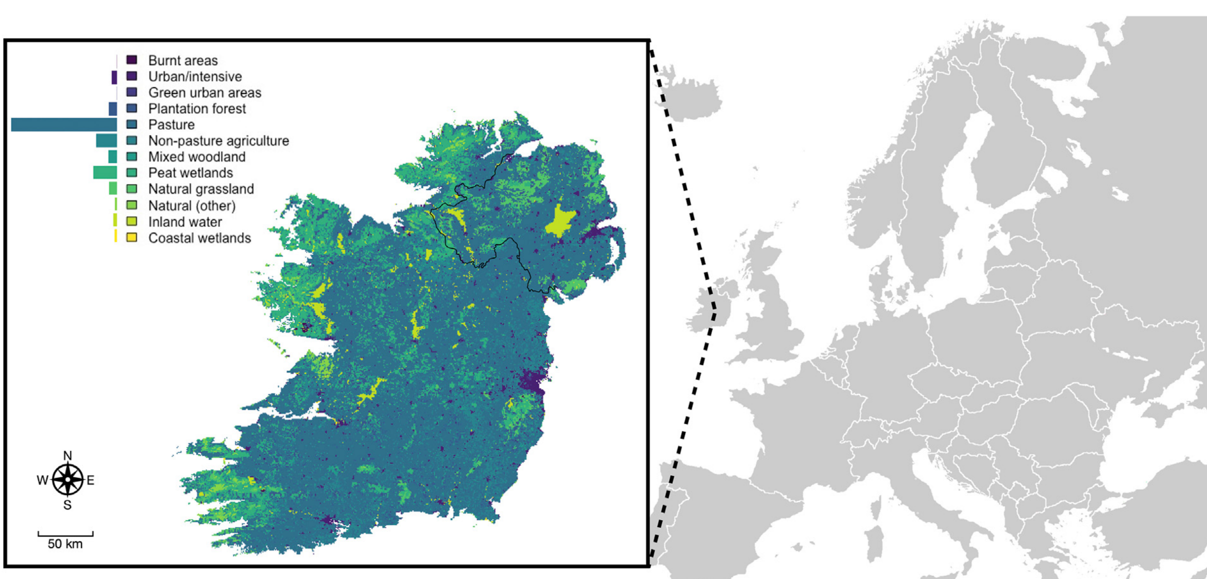

Fig. 1. Map of current land-use on the island of Ireland based on data from the CORINE land cover database obtained between 2012 and 2018. The histogram shows the proportion of land use in each category. The border between the Republic of Ireland and Northern Ireland is delineated with a black line.

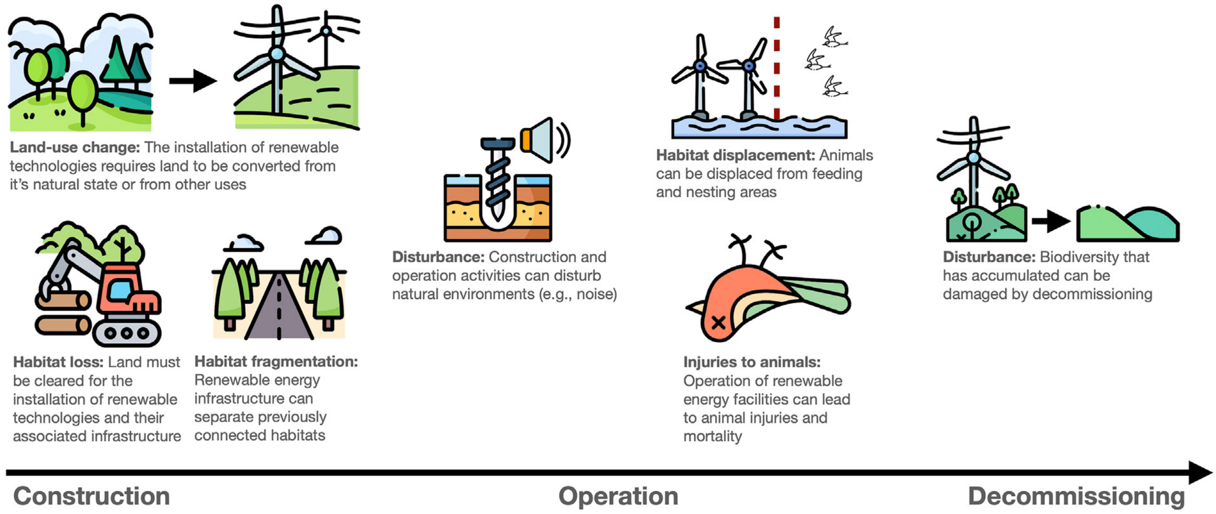

Fig. 2. Mechanisms for climate actions which impact biodiversity. We outline major mechanisms that could impact biodiversity during the three primary life stages of renewable energy facilities: construction, operation, and decommissioning.

(Kastelein et al., 2010; Lucke et al., 2009), if exposed at close range. Harbour seals (*Phoca vitulina*) have also been found to avoid wind farms during the pile driving, but return to the area shortly (within two hours) after the activity is ceased (Russell et al., 2016). The severity of these impacts is determined by the duration of the noise and the spatial dynamics of the marine mammal populations. Negative impacts can be minimised if animals are able to leave the immediate construction area throughout the duration of the pile driving activities. Several technologies exist to mitigate the noise emissions caused by construction activities such as noise reducing barriers (air bubble curtains) (Dähne et al., 2017; Lucke et al., 2011).

There are biodiversity considerations regarding the construction of onshore electrical infrastructure, such as substations. If placed inappropriately, they could disturb sensitive coastal or inland habitats and/or species. Environmentally sensitive areas should be avoided when determining the locations for these structures, which can be identified using existing technology such as sensitivity mapping tools (Burke, 2018).

Negative impacts during the offshore construction phase are short-term and there are several methods that can be used to mitigate negative effects on biodiversity. The use of "no take" exclusion zones around wind farms can mitigate negative effects in the short-term and promote long-term recovery of biodiversity stocks (Haggett et al., 2020). However, avoidance of constructing wind turbines in areas of high biodiversity value and/or important fishing stocks or nurseries should be practiced. Careful land and sea use planning using frameworks such as the National Marine Planning Framework (National Marine Planning Framework, 2021) are necessary to maximise potential positive impacts and minimise potential negative effects on biodiversity and climate.

2.1.2. Operation of offshore wind farms

Negative impacts on biodiversity during the operation stage will last for the entire lifespan of the wind turbine (~25 years). The primary concern relevant to Ireland is the impacts of wind turbines on seabirds, including collision mortality, habitat loss and displacement, and barrier effects (Cummins et al., 2019). Consistent with these potential impacts, offshore wind farms generally have a negative impact on seabird abundance (Stewart et al., 2007), and seabirds tend to avoid turbines during operation (Desholm and Kahlert, 2005; Petersen et al., 2006). This could indirectly result in habitat loss through reduced areas for foraging. Turbines could also act as physical barriers that impact the ability of birds to migrate or forage (Larsen and Guillemette, 2007). Birds can collide with the turbines, though collisions are generally thought to result in minimal mortality of birds in a population (Drewitt and Langston, 2006).

Most negative impacts can be mitigated or minimised by avoiding placement of wind farms in areas with sensitive habitats and populations of key species. In Ireland, more site-specific information is needed, including the distribution of key species, to accurately characterise the risk (Bowgen and Cook, 2018). Sensitivity mapping tools have been developed to identify areas of concern (Burke, 2018). It is especially important to avoid placing wind farms in areas important to seabird foraging and breeding. If sensitive areas cannot be avoided, an alternate solution would be to provide migration and foraging pathways between the wind farms by providing wide (several km) spaces free from turbines between wind farms (Goodale et al., 2019; Krijgsveld, 2014; Wilhelmsson et al., 2010). Regional planning of developments therefore needs to take the location and intensity of multiple wind farms into account.

Monitoring of seabird movements and occurrences prior to and during the construction and operation of offshore wind farms through GPS tagging, direct observation, and remote monitoring (acoustic, video, radar) techniques are needed to determine the potential for negative impacts and identify mitigation methods, including strategic curtailment of operations during times of high seabird activity (e.g., foraging or migration).

2.1.3. Decommissioning offshore wind farms

The decommissioning stage is an understudied component of offshore wind energy. It is, however, generally assumed that impacts will be similar to those in the construction stage (Gill, 2005; Vaissière et al., 2014). Options include complete or partial removal of turbines (Deeney et al., 2021). Complete removal would have similar impacts as the construction phase and could have negative impacts on biodiversity as the plants and animals that colonised the turbine foundations would be destroyed (Gill, 2005; Vaissière et al., 2014). A solution to this might be the partial removal of turbines, leaving the foundations intact. This could preserve the biodiversity that accumulated on the underwater structures. However, this would result in permanent fixtures on the seafloor and potential obstacles to shipping and fishing. An alternative is that the turbines could be continually maintained and upgraded as needed, so that removal is not necessary. Regardless, decommissioning plans should be drafted and continually updated as new technology becomes available and any decommissioning plans should consider potential impacts on biodiversity.

2.1.4. Offshore wind farm opportunities for biodiversity protection & restoration

With careful design, positive impacts relating to the development of offshore wind farms have been reported on marine biodiversity (Inger et al., 2009). Wind turbines and scour protection structures provide habitat and protection for marine wildlife such as fish and invertebrates (Leonhard and Pedersen, 2006; Wilhelmsson et al., 2006). Long-term studies from Denmark have shown that fish species abundance and diversity increased near turbines (Stenberg et al., 2015). Additionally, wind farms can be

Table 1
Key biodiversity impacts common to the four main renewable energy methods (offshore wind, onshore wind, solar, and bioenergy) with recommendations on how to avoid, minimise, and mitigate potential negative impacts.

Life cycle stage	General potential impacts	Offshore wind	Onshore wind	Solar	Bioenergy
Construction	• Land-use change • Disturbance • Habitat fragmentation • Habitat loss	1. Time development to minimise industry-wide impact during the construction of multiple wind farms. 2. Marine planning strategies such as the National Marine Planning Framework that explicitly include marine biodiversity protection and restoration are necessary. 3. Use existing sensitivity planning tools and develop new mapping tools to identify areas unsuitable for offshore wind in advance of construction. 4. Time construction to have the least possible overlap with important Cetacean migration, feeding, or breeding activities. 5. Implement floating wind farm technology to minimise sea-bed disturbance. 6. Assess pile driving effects in key spawning ground for fish stocks and use exclusion zones to promote recovery of stocks. 7. Use existing technology to reduce the noise created by construction activities (e.g., air bubble curtains). 8. Associated onshore support infrastructure for offshore wind should be developed with sensitivity to biodiversity impacts. 9. Design offshore infrastructure to provide habitat for biodiversity (artificial reefs).	1. New wind turbines (and repowering) should only be constructed in appropriate locations that do not compromise biodiversity or WFD obligations. 2. Avoid vulnerable and protected peatland and other nature protected areas. 3. Ensure that the site selection process and turbine placement is informed by the existing Special Areas of Conservations and Special Protected Areas, as well as the functional connectivity of isolated resources necessary for these protected sites. 4. Include migration pathways or commuting/foraging routes for key species in planning processes. Co-locate wind with more intensive agricultural land uses.	1. Solar panels should be incorporated into existing built infrastructure. 2. Farms of solar panels on agricultural or undeveloped land should be discouraged. 3. If utility-scale solar energy systems cannot be avoided, they should be strategically placed to avoid sensitive areas and minimise negative impacts on biodiversity.	1. Major land-use change should be avoided to minimise soil carbon losses (e.g., conversion of unimproved grassland to improved grassland or arable). 2. Avoid natural and semi-natural areas. 3. Prioritise the use of waste products for bioenergy.
Operation	• Habitat displacement • Injuries to animals	1. If a wind farm must be constructed in an important bird migration pathway, alternative migration corridors between wind farms must be available. 2. Monitor risk and risk avoidance measures (e.g., temporary curtailment) should be implemented. 3. Maximise positive biodiversity impacts of wind farm associated fisheries exclusion zones.	1. Encourage energy-environment/PFES/community schemes to promote enhancement of biodiversity in wider local landscape. 2. Real-time/smart monitoring to inform strategic curtailment during times of high bat and bird activity. 3. Community engagement in local biodiversity enhancement schemes.	1. The functional use of land beneath panels should be promoted (e.g., low intensity grazing). 2. Alternatives to herbicide use to manage vegetation below and between solar panels should be developed and used. 3. Management for tolerant elements of biodiversity between, around and beneath solar panels	1. Mandate the protection of important biodiversity landscape features (hedgerows, ponds, buffer strips, woodland edges etc.)
Decommissioning	• Disturbance • After-care or rehabilitation of decommissioned sites	1. Maintain and upgrade wind turbines as necessary to prevent or delay decommissioning. 2. Plan for decommissioning to maintain biodiversity benefits achieved through artificial reef formation.	1. Maintain and upgrade the wind turbines as necessary to prevent decommissioning.		

strategically located to protect areas that suffer from overfishing, as wind farms provide a barrier to fishing boats and trawlers. This would need to be monitored to track potential positive impacts.

2.2. Onshore wind farms

Onshore wind is currently the main renewable energy source in Ireland, with an installed capacity of 4.3 GW, with a planned increase to 8.2 GW by 2030. However, land-based wind farms can have significant negative impacts on biodiversity (Schuster et al., 2015), and there are important biodiversity considerations when placing new wind turbines as well as managing and repowering existing wind farms. While conflicts between wind farms and conservation areas are common, significant negative effects of the development of renewable energy infrastructure on biodiversity can be avoided with appropriate policy and regulatory controls (Dunnett et al., 2022). Appropriate siting of wind farms and early mitigation of key impacts during the construction stage have the greatest potential to reduce negative effects on biodiversity.

2.2.1. Constructing onshore wind farms

Wind farms are not as land intensive as some other sources of renewable energy (e.g., bioenergy). Determining the appropriate placement of wind farms is critical for avoiding the worst negative impacts. For example, inappropriate siting of a wind farm and failure to perform an EIA led to a major peat slide in county Galway in 2003, which severely impacted terrestrial and aquatic ecosystems (ECJ, 2008) with further slides in northwestern counties where wind farms were in the construction phases on peatlands. It is essential that wind farms and associated infrastructure, such as service roads, are placed in appropriate locations to avoid both direct and indirect impacts on biodiversity and water quality and that EIAs consider environmental risks such as peat slides to avoid future occurrences. This includes avoiding placement of wind turbines on deep and/or vulnerable peat soils. However, to be effective, wind turbines must be sited in areas where average wind speeds are high. This often leads to proposed sites in upland areas that can overlap with important habitats for birds (Drewitt and Langston, 2006).

Potential biodiversity impacts of onshore wind turbines and associated infrastructure such as service roads and buildings include vegetation disturbance, habitat loss, and habitat fragmentation. Construction of wind farms requires land to be cleared for infrastructure installation and ongoing servicing and vegetation such as trees and their associated biodiversity to be removed (van Haaren and Fthenakis, 2011). Grid connections require further development of land surrounding the wind farm.

2.2.2. Operation of onshore wind farms

The potential impacts during the operation phase are generally considered less severe than those caused during construction (Pearce-Higgins et al., 2012). The primary concerns are negative impacts on birds and bats, which are disproportionately affected by windfarms (Laranjeiro et al., 2018; Rydell et al., 2017; Schuster et al., 2015). Impacts include habitat loss and/or fragmentation, displacement from feeding or nesting areas, and injuries (including barotrauma and collisions) from turbines. Direct collisions are of particular concern as they can result in lethal and sublethal injuries affecting population viability (Grodsky et al., 2011). Bats are particularly vulnerable to fatality due to collisions (Rydell et al., 2017; Schuster et al., 2015), however the reasons for this are still poorly understood (Cryan and Barclay, 2009). In North America, the risk of bat collisions has been shown to be strongly influenced by weather (Arnett et al., 2008; Baerwald and Barclay, 2011), indicating that curtailing wind farm operation during certain weather conditions could potentially prevent fatalities, but this requires testing. Additionally, turbine placement has some influence on fatality risk, as the highest fatality rates are generally attributed to turbines located at the ends of turbine strings (Arnett et al., 2008). Ireland has nine species of bats, all of which are protected under the Wildlife Acts 1976–2021 and Annex IV of the Habitats Directive. Three bat species are considered high risk in relation to turbines (EUROBATS, 2014; Mathews et al., 2016), with Leisler's bat (*Nyctalus leisleri*) considered internationally important as Ireland is a stronghold for the species (Marnell et al., 2009).

It is important to obtain damage estimates from all levels of wind farm operation to mitigate negative impacts on-site and to inform future development. Estimates of the number of fatalities per turbine and per wind farm, are needed so that cumulative, industry-wide, damage to populations can be predicted. Total national population estimates should be continuously updated based on the results of action-based monitoring. Differences in life histories between birds and bats (Healy et al., 2014) mean that effort is needed to identify impact threshold limits which are appropriate for different groups of species.

Some birds are vulnerable to habitat loss, displacement, and increased mortality due to collisions. In Ireland, the Hen Harrier (*Circus cyaneus*) is a particular species of concern. Hen harriers are raptors that live and breed in upland areas that often overlap with existing and potential wind farms (Fernández-Bellon et al., 2015). This species is listed on Annex 1 of the EU Birds Directive, so Ireland is responsible for maintaining its favorable conservation status. Generally, bird mortality has been found to be relatively low due to collisions with wind turbines (Drewitt and Langston, 2006), however long-term, active monitoring is needed to determine whether these low mortality rates are more significant for long-lived species with slow maturation and low reproductive rates, such as raptors. Studies of the interactions between raptors and wind farms outside of Ireland have found that raptor abundance decreased 47 % after the construction of wind turbines (Garvin et al., 2011), and that raptors often demonstrate avoidance behaviors at wind farms that could lead to habitat loss via displacement (Dohm et al., 2019; Garvin et al., 2011; May, 2015). There is some evidence that these negative impacts are diminished over longer time scales (Dohm et al., 2019). It is also possible that the Hen Harrier could be negatively impacted by a reduction in available prey species due to wind farms (Fernández-Bellon et al., 2019), further indicating the need for active monitoring of prey populations and associated habitat management throughout the lifespan of wind farms.

Appropriate site location is considered to be the most important method for mitigating negative impacts on birds and bats (Hötker et al., 2005). For example, sites in areas with high occurrence rates of raptors should be avoided as wind farm sites (Hötker et al., 2005). Mortality due to collisions could potentially be lessened through modifications in turbine design, placement, and operation (Dai et al., 2015). Turbine height and placement have a significant impact on collision risk, with taller turbines and turbines at higher elevations resulting in higher collision mortality (Lucas et al., 2008). Strategic arrangement of turbines within the sites can further reduce negative impacts (Drewitt and Langston, 2006).

Impacts to birds and bats could be potentially mitigated during operations; however, these are less well developed. Temporary curtailment of turbines during high-risk conditions for bat and bird collisions may help to reduce fatalities (Arnett and May, 2016; Lagrange et al., 2013; Smallwood and Bell, 2020) without compromising turbine performance and energy output (Rogers, 2020).

2.2.3. Decommissioning onshore wind farms

In the decommissioning phase, similar disturbances as found in the construction stage can be expected if the turbines are removed. Extending the lifespan of turbines through retrofitting and repowering can also minimise displaced construction impacts at new sites. Repowering can present challenges however, as sites that were previously licensed may subsequently be recognized as unsuitable, due to biodiversity and habitat impacts. Active habitat restoration and/or rehabilitation may be needed to mitigate negative biodiversity impacts of decommissioning.

In terms of long-term impacts on habitats, where road infrastructures are maintained on upland peatland sites this can lead to ongoing degradation due to drying out of the peat and fragmentation of the habitat. Overall, the general consensus is that to avoid impacts on habitats – through all stages – peatland areas should be avoided (Renou-Wilson and Farrell, 2009). Where existing peatland site are being decommissioned, an appropriate rehabilitation and restoration plan should be legally required and implemented.

2.2.4. Onshore wind farm opportunities for biodiversity protection & restoration

When implemented appropriately, the development of onshore wind presents opportunities for biodiversity restoration and protection (Fig. 3). Mitigation by avoidance is key for vulnerable habitats and species; followed by mitigation by rehabilitation and/or creation of habitats in areas surrounding wind turbines. Those areas previously functioning as carbon sinks that help regulate climate (i.e., peatlands) can be managed to provide habitat for various plant and animal species. The ecological potential of each site will vary according to its natural state, level of degradation, and constraints on biodiversity imposed by the wind turbine operation, therefore optimal rehabilitation and management practices need to be developed for each site. However, rehabilitating degraded habitats can be done in a way to not only promote biodiversity, but with good ecological guidance can also considerably reduce potentially negative impacts for climate and water quality.

Wind farms could also be co-located with areas already under intense land-use, such as agriculture or forestry. However, the availability of wind energy and willingness of landowners/managers to support wind farm installations on land with higher productivity value need consideration.

a)

b)

Fig. 3. Opportunities for biodiversity restoration and protection. a) photo of an Irish wind farm where the natural habitat surrounding the wind farm was rehabilitated; b) photo of an Irish wind farm that is co-located with intensive agriculture.

2.3. Solar photovoltaics (PV)

The 2021 Climate Action Plan includes increasing energy produced via solar photovoltaics (PV) to 1.5–2.5 GW of installed capacity by 2030 from a relatively low base of 0.024 GW in 2018, a 63–104 fold difference (SEAI, 2020). The scale of PV installations varies greatly, from distributed solar energy systems installed on rooftops of residential houses or commercial buildings, to utility-scale solar energy systems that occupy large areas of land. Distributed solar energy systems are relatively small in capacity (<1 megawatt [MW]) and are generally built into existing infrastructure, where they are likely to have negligible adverse impacts on biodiversity (Dale et al., 2011). Therefore, initiatives such as the microgeneration grant scheme for PV designed to promote the installation of solar panels on individual homes (Government of Ireland, 2021) should continue to be developed and supported. However, utility-scale solar energy systems are large-scale, high-capacity (>1 MW) operations that have far greater potential to affect biodiversity due to land-use change. It is estimated that current PV technology requires about 1.4–6.2 ha of land per MW of electricity production (U.S. Department of Energy, 2012; Walston et al., 2016). According to these estimates, if Ireland was to employ only utility-scale solar energy facilities to reach their Climate Action Plan target of 1.5 GW of capacity, a minimum of 2250 ha of land would be needed. The large land area requirements of solar PV have many potentially negative impacts on biodiversity (Hernandez et al., 2014; Macknick et al., 2013), including key impacts such as habitat loss and fragmentation.

2.3.1. Construction of solar PV farms

The construction of utility-scale solar facilities requires the conversion of existing agricultural areas to solar farms, or the diversion of other land-uses. There are potential consequences for biodiversity for either of these land-use options since land-use change to more intensive uses generally has negative impacts on biodiversity (Newbold et al., 2015). The conversion of existing agricultural land to solar farms could displace previous agricultural activity to less intensively farmed or semi-natural areas (Hernandez et al., 2014), with negative consequences for native plants and animals through resulting habitat loss and fragmentation (Fahrig, 2003; Hernandez et al., 2015b). The negative impacts of habitat loss and fragmentation are potentially exacerbated further during the construction of transmission lines and corridors (Andrews, 2014). However, the effects on biodiversity could be positive when converting low diversity land-uses, such as arable fields or intensive pasture, to solar farms, if wildlife management is prioritized (Montag et al., 2016).

Siting solar facilities in areas already degraded and/or developed by humans (such as the built environment) can reduce the magnitude of adverse impacts (Hernandez et al., 2015a). Outside of the built environment, care must be taken so that land use change, habitat loss, and habitat fragmentation are minimised and that solar farms are not placed in sensitive areas or areas acting as carbon sinks as solar panels reduce productivity through light and rainfall interception (e.g., peatlands and semi-natural grasslands in Ireland) (Hernandez et al., 2015a, 2014).

Construction of utility-scale solar energy systems requires land development, including clearing the existing vegetation and grading the soil (Macknick et al., 2013), leading to direct environmental impacts such as soil disturbance, habitat loss, degradation, and fragmentation (Hernandez et al., 2014; Macknick et al., 2013). Construction can have indirect impacts such as changes in water quality due to soil erosion, herbicide application and facilitating the spread of invasive species.

Some negative impacts of solar PV installation could potentially be mitigated through actions such as the promotion of functional land use beneath the panels and maintaining natural habitat within the landscape matrix. For example, planting native plant species which can tolerate the altered conditions beneath and between solar panels can create habitat for pollinators (Graham et al., 2021). However, direct and indirect habitat loss is much more difficult to mitigate. Some habitat loss could potentially be mitigated through compensation by restoring and/or rehabilitating natural areas elsewhere. This kind of offsetting should, however, be considered only as a last-resort (Simmonds et al., 2020). To guide policymakers there should be a clear view of trade-offs between the benefits of semi-natural habitat versus clearance for solar installations, as it is likely that grants to install solar sites could drive further habitat loss.

2.3.2. Operation of solar PV farms

The potential negative impacts of utility-scale solar facilities on biodiversity are significant during the operation stage (Hernandez et al., 2014). The installation of solar panels alters the composition of plant species that can colonise and persist in solar farms, as they reduce the amount of available light and water and influence microclimate beneath the panels. Arrays of solar panels can also cause seasonal and diurnal variation in air and soil microclimate that could scale up to affect plant-soil processes and carbon cycling (Armstrong et al., 2016, 2014). Both above-ground plant biomass and plant species diversity are lower under solar panels, and these differences can be explained by variation in microclimate and vegetation management (Armstrong et al., 2016).

Facilities regularly apply herbicide during the operation stage to prevent the regrowth of vegetation that was cleared during construction to avoid shading of the panels, pests, and reduce the risk of fires (Macknick et al., 2013). There are several potential negative impacts associated with regular herbicide use, including off-target effects in wild plant communities (Russo et al., 2020), detrimental effects on pollinators (Cullen et al., 2019; Zioga et al., 2020), and water pollution (Abbasi and Abbasi, 2000). There are also concerns that these systems could generate even more problematic water pollutants as several toxicants are used during operation and maintenance, including coolants, antifreeze, and rust inhibitors (Abbasi and Abbasi, 2000; Tsoutsos et al., 2005). The panels themselves contain toxic heavy metals, such as cadmium sulphide, that could potentially leach from the panels (Abbasi and Abbasi, 2000). Clearly, monitoring the impacts on existing solar sites would inform the potential risks in future sites.

It is possible that birds could collide with solar panels. However, previous work found that mortality due to collisions was negligible relative to population sizes (McCrary et al., 1986, Mojave Desert). The impacts of utility-scale solar energy facilities on avian mortality in the United States are, however, estimated to be similar to those in the wind energy sector (Walston et al., 2016). As the development of utility-scale solar is in its infancy in Ireland, more work is needed to be able to accurately predict the effects of these facilities on Irish birds.

2.3.3. Decommissioning solar PV farms

The primary impact of concern during the decommissioning stage would be pollution of the environment with toxic materials contained within the solar cells due to damaged cells or improper recycling (Fthenakis et al., 1984). However, these risks can be prevented almost entirely by following waste handling regulations (Fthenakis, 2000).

2.3.4. Solar PV opportunities for biodiversity protection & restoration

The development of solar PV offers limited opportunities for biodiversity protection and restoration. There are, however, opportunities to create functional space beneath solar panels to support pollinator communities (Blaydes et al., 2021; Dolezal et al., 2021), but this would have to be considered on a site by site basis. However, almost all potential negative impacts of developing solar can be avoided by limiting its deployment to the built environment. This includes incorporating solar panels into existing infrastructure such as buildings, car parks, and residential houses. Initiatives such as the micro-generation grant scheme for PV are already in place to promote the installation of solar panels on individual homes in Ireland (Government of Ireland, 2021), and such programs should continue to be developed and supported. For larger developments, siting solar facilities in areas already degraded and/or developed by humans can reduce the magnitude of adverse impacts (Hernandez et al., 2015a). Therefore, taking a “right action, right place” approach by limiting solar facilities to the built environment could be a significant win-win for climate and biodiversity in Ireland (Joshi et al., 2021).

2.4. Biofuel cultivation

Biofuels, such as biogas and biomethane, are emerging technologies that could be used as a climate mitigation strategy. Biogas is produced from the decomposition of organic materials (i.e., feedstocks) such as energy crops, residues, and wastes (Weiland, 2010). These feedstocks are placed in a digester system that takes advantage of naturally occurring anaerobic digestion to break down the waste and produce gases, such as methane. This process produces a renewable biogas that can be used for a variety of applications such as producing heat and power (Achinas et al., 2017). The biogas can be further refined into biomethane, which can then be injected into natural gas pipelines or used to fuel vehicles. Ireland's bioenergy resources consist of forestry by-products, organic wastes, and energy crops. Energy crops with potential to be cultivated for biomass in Ireland include wheat, oil seed rape, short rotation coppice, willow, *Miscanthus*, and grass silage (Sustainable Energy Authority of Ireland).

Several lines of international evidence indicate that bioenergy has potential to be poorly implemented, leading to this sector directly and indirectly producing even more greenhouse gas emissions than traditional fossil fuels (Dauber et al., 2010; Searchinger et al., 2009). For example, the conversion of carbon rich ecosystems (e.g., tropical forests or peatlands) into biomass plantations leads to the release of previously sequestered carbon into the atmosphere, resulting in a carbon debt that could take >100 years to pay back (Gibbs et al., 2008; Searchinger et al., 2008). The production of bioenergy crops could also lead to increases in greenhouse gas emissions via land-use change, as bioenergy plantations often displace agriculture into natural habitats such as forests and grasslands (both locally and internationally) (Searchinger et al., 2015, 2008). Farmers may also attempt to replace agricultural land lost to biofuel by increasing the yields from remaining croplands, leading to increased usage of water and fertiliser (Searchinger et al., 2015, 2008).

There is a pressing need for short-term sources of sustainable liquid and gas fuels, particularly for transport, with electrification of the heating and terrestrial transport sectors likely to largely displace biofuels in these sectors in the medium term. In the Climate Action Plan, bioenergy is classed as an emerging technology with need for targets for production to be set according to feedstock supply issues. The development of bioenergy could have significant negative impacts on biodiversity depending on which land-use it replaces, what bioenergy crop is grown, and how it is managed. The primary concerns are that the cultivation of bioenergy crops and creation of biomass plantations are land-use intensive (Beringer et al., 2011; Fritsche et al., 2010). It should be noted that agricultural land-use, with associated habitat destruction and nutrient leaching, is currently the most prevalent threat to habitats, biodiversity and freshwater quality in Ireland (NPWS, 2019) and globally (IPBES et al., 2019). It is likely that expansion or intensification of agricultural land-use through bioenergy cultivation will further impact biodiversity.

2.4.1. Conversion of land-use to bioenergy crops

Of renewable energy sources, the biomass cycle has the greatest demand for land (Fthenakis and Kim, 2009). In Ireland, existing agricultural land would need to be converted to produce bioenergy crops, additional land developed for agriculture, or existing feedstocks (grass) diverted from livestock to biofuel production. Converting existing agricultural land to produce bioenergy crops and/or developing additional land for agriculture would bring significant land-use changes, which generally expedites biodiversity loss (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, 2018; Newbold et al., 2015; Sala et al., 2000). Negative biodiversity impacts are generally expected when natural and semi-natural areas (e.g., unimproved semi-natural grasslands) are converted to biomass plantations. The conversion of existing grass feedstocks from livestock to biofuel production might seem the best option for climate and biodiversity, if livestock farming is not displaced to other areas resulting in the intensification of high nature-value farmland and that imported feedstocks are not used as a replacement to sustain livestock instead.

There are several advantages to using grass as a feedstock in Ireland. For example, arable land is not needed for growing grass and farmers are already familiar with growing it, as over 90 % of Ireland's agricultural land is under grass (Smyth et al., 2009). Were livestock production systems to be disincentivised due to their high methane production to meet Climate Action Plan targets for the agricultural sector, then alternative land-uses for former pasture will need to be considered. There are, however, potential biodiversity impacts of grass to biomethane systems. The main concern is that the higher value of grass crops due to waste valorisation may drive further land-use change and intensification.

2.4.2. Operation of biofuel cropping

The cultivation of bioenergy crops, as with other intensively farmed arable crops, can negatively impact soil by increasing erosion, reducing soil organic carbon, and therefore decreasing soil fertility. Soil organic carbon is an important indicator of soil quality and productivity, with higher values corresponding to better soil water retention, higher soil biodiversity, and higher productivity. Soils are also important carbon sinks, as the soil organic carbon is sequestered instead of being released into the atmosphere. There are three main ways that the cultivation of energy crops can negatively impact soil: land-use change, tillage, and residue removal (Wu et al., 2018). For example, the initial conversion of undisturbed soil to tilled can result in 20–40 % loss of soil carbon during the first 5–20 years of cultivation (Davidson and Ackerman, 1993), however, this is not universal (Zimmermann et al., 2012). Furthermore, harvesting crop residues (i.e., dead plant material left after harvesting) can also lead to soil erosion, have negative impacts on soil fertility, and reduce soil carbon, resulting in carbon dioxide emissions (Liska et al., 2014). Some of these negative impacts could potentially be mitigated by locating bioenergy crops in areas with already degraded soils and using conservation tillage practices that leave a percentage of crop residues in place to be broken down naturally (Hoekman et al., 2018).

The impacts of bioenergy crop cultivation vary in type, magnitude, and scale, depend on the crop grown, and are difficult to generalise. For example, responses to bioenergy crops differ among pollinator taxa (Stanley and Stout, 2013), and effects on species vary depending on which crops were replaced by bioenergy crops (Stanley and Stout, 2013). Further context specific research on taxa and landscapes is clearly needed to better understand how the development of bioenergy through different land use changes could impact local biodiversity. Due to the large areas of land that would be required to meet energy production targets via bioenergy, the spatial layout and distribution of such areas would determine the extent of negative impacts (Dauber et al., 2010).

Optimisation of biomethane production from grass would likely require the inputs of fertiliser, herbicide, and lime to agricultural fields (Smyth et al., 2009). These inputs would negatively impact native plants and animals, and result in additional detrimental impacts to aquatic ecosystems and groundwaters (Abbasi and Abbasi, 2000). More research is needed on the quality of the biomass inputs for biomethane production (e.g., single species versus multi-species swards) and sustainable management practices that avoid fertiliser and pesticide use. Some negative impacts could potentially be mitigated by incorporating the protection of important biodiversity landscape features, such as hedgerows, ponds, and buffer strips, into plans to expand the development of bioenergy.

2.4.3. Biofuel opportunities for biodiversity protection & restoration

The development of bioenergy in Ireland provides some opportunities for biodiversity protection and restoration. For instance, the development of this sector in Ireland may generate further pressure to develop innovative methods for sustainable agriculture, which could be beneficial for other renewable energy projects. Additionally, there is the possibility of incorporating biodiversity landscape features into bioenergy land uses, which should generally be encouraged.

3. Afforestation and habitat restoration as climate mitigation strategies

Forests account for about 10.8 % of the land area in Ireland (Department of Agriculture, Food and the Marine, 2014). The Climate Action Plan aims to plant 8000 ha of new forest each year to reach an ultimate target of 18 % cover by 2046 (Government of Ireland, 2021). This will be achieved through planting and natural regeneration (Government of Ireland, 2021).

3.1. Afforestation through plantations, woodland restoration, hedgerow retention, management, and expansion

Reforestation and afforestation are considered to be relatively cost-effective climate mitigation strategies (Fuss et al., 2018) as forests can slow the accumulation of greenhouse gas emissions by sequestering carbon (Rudel et al., 2005). In addition to the short-term carbon sequestered during tree growth, there is also the potential for long-term carbon storage in urban structures by replacing carbon-intensive materials such as concrete and steel with engineered timber (Churkina et al., 2020). If appropriate tree species are planted on the right soils, this afforestation target could have substantial positive impacts on biodiversity and water quality. Implementation is, however, key to maximising these positive effects (Allen and Chapman, 2001; Sacco et al., 2021).

Like other climate mitigation methods, siting is critical for increasing the positive biodiversity impacts of afforestation and minimising the potential negative impacts (Sacco et al., 2021). For example, afforestation of naturally open areas of high biodiversity value (e.g., peatlands and semi-natural grasslands in Ireland) could have adverse impacts on the ecosystem and potentially result in the loss of distinctive species (Abreu et al., 2017; Wilson et al., 2014). In Ireland, the Hen Harrier is a sensitive species that has already experienced habitat loss due to afforestation of large areas of natural open habitat (O'Leary et al., 2000). Current afforestation is heavily weighted towards monocultures of non-native species harvested for timber use with short usage lifespans which has limited value for both climate change mitigation and biodiversity. There are plans to continue to afforest areas of open habitat in Ireland with commercial non-native species, which would likely cause further damage to Hen Harrier habitat with limited positive biodiversity impacts. Rehabilitating and restoring degraded forests to natural and semi-natural states would be much more effective for conserving biodiversity while also contributing to climate mitigation targets.

It is estimated that about a third of peatlands are drained for forestry in Ireland (Connolly, 2018). Several of these sites have resulted in low-productivity forests, or failed plantations on deep peat and heathland slopes, some of which are carbon sources (Jovani-Sancho et al., 2021). In addition to ceasing afforestation efforts in habitats with peat soils, restoration of peatlands where possible would benefit both biodiversity and climate by reducing soil carbon emissions and promoting native biodiversity. Some work has been carried out on restoring peatlands post-felling of conifer plantations in Ireland and the UK, and this work should be supported and monitored to set realistic targets based on restoration trials (Andersen et al., 2017).

When sited appropriately, it is also important to consider the species used for afforestation. Native Irish forests consist of primarily mixed deciduous tree species (Cross, 1998). However, current afforestation schemes (except The Native Woodland Establishment Scheme) plan to plant monocultures of commercial, non-native, coniferous trees, such as Sitka Spruce (*Picea sitchensis*). A wide body of evidence shows that monocultures provide limited biodiversity value (Altieri, 1999; Felton et al., 2010; Iezzi et al., 2018) although, they can host species of conservation concern (Irwin et al., 2013). Furthermore, their effectiveness at sequestering carbon over long timescales has been questioned (Körner, 2017; Lewis et al., 2019). Commercial monocultures may be effective at carbon sequestration in temperate environments (Forster et al., 2021), but depends on the soils (Jovani-Sancho et al., 2021). Monocultures are more vulnerable to natural disasters such as pest outbreaks than mixed forests (Verheyen et al., 2016), which makes them risky as a carbon storage mechanism. Alternatively, forests composed of native mixtures have a high capacity to promote biodiversity through creating habitat for wildlife and attracting pollinators and seed-dispersing animals (Sacco et al., 2021; Twining et al., 2022) and could be more resistant to pests (Verheyen et al., 2016). The resilience of forests to natural disasters, such as pest outbreaks, is an important consideration for both climate mitigation and biodiversity. To maximise future resilience, it is important to not only plant a diversity of species, but also to identify genotypes and species that might be particularly robust to threats and/or changing climatic conditions. A balance of commercial monocultures and mixed native forests could be a bet hedging strategy for climate mitigation and biodiversity. However, afforestation efforts would have the greatest positive impact on biodiversity if a mix of native trees were used (Lewis et al., 2019; Sacco et al., 2021).

The species used in afforestation projects also impact the surrounding environment, including freshwater ecosystems. For example, afforestation can have an acidifying effect on streams, largely due to the abilities of forest canopies to act as ‘pollutant scavengers’ (i.e., they enhance the capture of acidic pollutants such as nitrogen and sulphur). Coniferous trees, such as Sitka Spruce, are particularly problematic as they are efficient pollutant scavengers and also form an acid litter layer (Department of the Environment, 1991; Nisbet and Evans, 2014). This is especially harmful in “acid-sensitive” areas where the natural geology (e.g., shale, granite, and sandstone) already has an acidifying effect on streams (Collier and

Farrell, 2007). Commercial coniferous plantations have the potential to exacerbate existing water quality issues, which could compromise obligations to improve water quality via the EU Water Framework Directive (2000/60/EC).

Increased afforestation could lead to a higher frequency of forest fires that would damage biodiversity and release carbon into the atmosphere. This could happen for several reasons. For example, if wetland areas (e.g., peatlands) that have a naturally low risk of fire are afforested, trees can dry up the wetlands via transpiration and increase the risk of fire in previously wet habitats. Commercial monocultures are particularly at risk for severe fires (Odion et al., 2004), highlighting another advantage of planting native mixtures. Current Common Agricultural Policy rules incentivise the removal of scrub (e.g., gorse and heather) to keep land in good agricultural condition for eligibility of farm payments. This leads to fires being set to clear land and these fires can spread to forests, leading to erosion of peat soils, and carbon release. It would be beneficial for biodiversity and climate mitigation if the Common Agricultural Policy rules could be adapted and enforced to protect sensitive habitats from fire and provide for buffers around at-risk sites (i.e., disincentivise clearance of land with biodiversity value). Buffer areas might also function as corridors for native plants and animals that could promote biodiversity (Altieri, 1999).

Hedgerows and other woodland habitats are an important part of the Irish agricultural landscape accounting for ca. 5 % of the area of intensive farms (Larkin et al., 2019) and up to 11 % on extensive farms (Rotchés-Ribalta et al., 2021), providing a valuable ecological network and habitat in the agricultural landscape. The ecosystem services delivered by hedgerows include carbon sequestration and storage, pollutant remediation, shelter for livestock and aesthetic appreciation of the landscape. Given the large areas under hedgerow, treelines, woodland copses, and scrub, the carbon storage and sequestration ecosystem services at a national scale are substantial. Hedgerows have annual carbon sequestration estimates of 0.5–2.7 tCO_2/ha/yr (Black et al., 2014; Green et al., 2019). The carbon estimated to be stored in hedgerows and woody habitats represents a significant store of carbon at the national scale that needs to be appropriately managed to ensure the stored carbon is not released back into the atmosphere.

More research is needed to assess whether hedgerow management is an effective land-use mitigation strategy (Green et al., 2019). Resolving this uncertainty is a priority as the potential for hedgerows and woodlands on agricultural land to be an effective mitigation strategy is high. Data from LiDAR surveys can be used to quantify the carbon sequestration of hedgerows ("Farm Sustainability Plan - Teagasc | Agriculture and Food Development Authority," 2021). Annual surveys throughout the lifetime of the project would generate the most useful data, estimating carbon sequestration in woodland, hedgerow, and scrub farmland habitats to build certainty.

3.2. Afforestation opportunities for biodiversity protection & restoration

There is high potential for agroforestry (i.e., the intentional integration of trees and shrubs into crop and animal farming systems) to provide climate and biodiversity benefits. The goal of agroforestry is to combine agriculture and forestry in a mutually beneficial way. Agroforestry can increase landscape diversity and promote biodiversity. Additionally, it has positive benefits for water, as it provides for land drainage through increased transpiration, hinders nutrient runoff, and reduces sedimentation in aquatic systems near farms. Agroforestry can also have positive impacts on livestock by providing shade and shelter from rain and wind. Agroforestry can increase soil health by enriching soil organic carbon, improving soil nutrient availability and soil fertility, and promoting soil microbial diversity and activity (Dollinger & Jose, 2018). It can also increase the availability of foraging resources and habitat for wild bees (Kay et al., 2020). Incorporating flowering trees into grassland agriculture could, therefore, promote pollinator diversity and enhance pollination services available in agroforestry systems. However, the implementation of agroforestry is key for optimising the positive biodiversity benefits. The use of native trees in agroforestry practices should be encouraged, together with trees planted to increase landscape connectivity and act as buffers along riparian margins.

Hedgerows and woody habitats on farmland represent a vital ecological network supporting biodiversity in the agricultural landscape. Meeting the EU's 2030 Biodiversity Strategy's target of 10% of farmland area being 'high diversity landscape features' would thus represent a protection of existing biodiversity, restoration of biodiversity on intensive farms where habitat cover tends to be particularly low, and an increase in the sequestration and carbon storage associated with hedgerows and woody farmland habitats, increasing further the effectiveness of these semi-natural habitats as an important land-use mitigation strategy.

3.3. Restoration and rehabilitation of native habitats

3.3.1. Peatland restoration and rehabilitation

Peatlands are biodiversity hotspots that provide habitat for unique plant and animal species. Ireland is a global hotspot for peatlands, and peatlands and peat soils extend to over 20 % of its land area. Peatlands are complex ecosystems that have aided in climate regulation for millennia by acting as large carbon sinks (Joosten et al., 2016). While healthy peatlands store large amounts of carbon, damaged peatlands are a major source of greenhouse gas emissions and it is estimated that they will be responsible for 8 % of anthropogenic CO_2 emissions by 2050 (Urák et al., 2017). Their significance for biodiversity conservation and climate mitigation, however, has not always been realised, and longstanding efforts to drain and use peatlands for agriculture and forestry has resulted in large scale degradation of peat habitats throughout Ireland. This has resulted in the loss of unique species, and ultimately decreased the potential of Irish peatlands to contribute to climate mitigation through loss of soil carbon due to drainage and planting (Jovani-Sancho et al., 2021).

In addition to the peatland areas that were drained for agriculture and forestry, about 5–6 % of peatlands have been drained for industrial peat extraction. Negative impacts of peat extraction for climate and biodiversity have long been recognized and peat extraction for fuel on state managed lands has recently ceased. Many of the state owner industrial extracted areas will be decommissioned and rehabilitated as part of a state funded program to reduce greenhouse gas emissions, with the added benefit of regeneration of semi-natural wetland habitats. This equates to only ca 5 % of the national peatland resource, so a full inventory of peatlands should be considered in terms of potential wins for rewetting (Farrell et al., 2022).

There is, however, still demand for, and extraction of, horticultural peat at a commercial scale. Smaller scale regional and domestic turf extraction is also ongoing for use in home heating. Cessation of commercial extraction could displace peat extraction to bogs that lack licensing and regulations with negative impacts for both biodiversity and climate mitigation. Regulation of peat extraction (including turf for fuel) would help prevent the expansion of extraction, and resulting consequences for climate, water, and biodiversity (Farrell et al., 2022). Furthermore, the rehabilitation of decommissioned bogs should be a top priority for climate mitigation and biodiversity conservation in Ireland as this is a Nature Based Solution that would deliver multiple co-benefits for the environment (Farrell et al., 2021b). Policy to enable a just transition from peat extraction to other economic activities and to alleviate fuel poverty in regions where peat is used for heating are urgently needed.

3.3.2. Rewetting drained soils

A large proportion of farms in Ireland are located on land that is poorly drained due to natural factors such as soil type, topography, and climate. Teagasc estimates that 30 % of the 3.18 million hectares of nationally managed grassland is imperfectly or poorly drained (Teagasc, 2021). Such poorly drained soils are suboptimal for farming as they remain wet for prolonged periods, resulting in shorter grazing seasons, and lower productivity and profitability. To improve the profitability of grassland farms on heavy soils, Teagasc implemented a 'Heavy Soils Programme' that aims to drain 10 % of Ireland's total grassland by 2030 to increase the quality of agricultural land. It has also been suggested that this program will be beneficial for climate mitigation as the drainage of mineral soils can result in a direct reduction of N_2O emission. However, the benefits for climate mitigation are limited, as draining organic and/or peat dominated soils results in significant emissions of the CO_2 that is naturally sequestered in such soils. The drainage of mineral soils could also lead to an increase in N leaching (Teagasc Greenhouse Gas Working Group, 2019). There are also substantial potentially negative impacts that could result from this scale of soil drainage due to the significant overlap between heavy soils and high nature-value farmland ("HNV Distribution," 2015). Draining of heavy soils and subsequent intensification of livestock farming will likely reduce the distribution and coverage of high nature value farmland, and therefore negatively impact biodiversity.

Teagasc have included rewetting 40,000 ha of organic grassland soils (out of a total 370,000 ha of drained organic soils) as a possible climate mitigation method in the second iteration of the Greenhouse Gas Marginal Abatement Cost (Teagasc Greenhouse Gas Working Group, 2019). This action would likely have positive effects on biodiversity and climate. For example, Teagasc has estimated that stopping drainage and restoring natural water tables for 40,000 ha of grassland would result in an emissions savings of 0.44 metric tons of carbon dioxide equivalents (CO2-e) per annum (Teagasc Greenhouse Gas Working Group, 2019). As a significant number of emissions (1.4 Mt CO2-e) are generated from drained sites within protected areas, it would be especially beneficial for both climate and biodiversity to rewet protected sites. As an alternative to stopping drainage and completely rewetting 40,000 ha of grassland, Teagasc proposes that converting 65,000 ha of nutrient-rich managed grasslands from deep drained to a shallow drained state could result in a similar amount carbon savings. Were ambitions increased and both of these measures applied, there would be substantial benefits to both climate and biodiversity. The rewetting of peaty agricultural soils could be a large land use abatement measure and would also provide habitat for many native plant and animal species.

4. Conclusions

Major action is urgently needed to prevent the devastating impacts of unimpeded climate change, but these measures must be implemented in a way that does not put further pressure on biodiversity. Here, we provide a set of considerations for the achievement of biodiversity goals through climate actions. While the optimal implementation of these actions will vary nationally and regionally, we have identified several considerations that are consistently important for maximising the potential benefits for climate change and biodiversity loss mitigation. The synergies presented here are not exhaustive and there are other win-win actions, especially regarding societal changes to combat climate change that would undoubtedly have a positive impact on biodiversity. For example, building a sustainable food system with climate- and biodiversity-friendly agricultural practices, responsible food trade, and equitable food distribution (InterAcademy Partnership, 2021) would benefit biodiversity. Future discussions should detail these potential co-benefits.

Ultimately, the solutions to the climate and biodiversity crises must be integrated, and biodiversity considerations should be incorporated into land use management through a natural capital accounting approach. This requires that we bring ecological considerations for all renewable energy plans and projects to the design phase. This strategy facilitates avoidance of biodiversity conflicts with national strategic infrastructure works, as obstacles can be eliminated in advance.

Biodiversity-friendly renewable energy can be achieved by prioritising renewables that are least damaging and ensuring that infrastructure development is carried out as sensitively as possible to protect, restore, and enhance biodiversity. We should promote renewable energy methods with the lowest negative ecological impacts, such as offshore wind and the incorporation of solar into the built environment. Additionally, appropriate location of sites is critical for all renewable energy projects. It is important that projects are implemented so they do not compromise biodiversity and have unintended negative effects on carbon emissions. To ensure best practices and accountability, we need action-based monitoring for all measures. The monitoring processes need to focus on an action response model if impacts are identified, rather than the current scenario where damage is recorded year after year with little to no action.

This case-study provides one of the first examples of how climate actions can be implemented in a biodiversity-conscious way. With careful planning, we can synergistically mitigate both our climate and biodiversity crises.

CRediT authorship contribution statement

Courtney E. Gorman: Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Project administration, Visualization. **Andrew Torsney:** Conceptualization, Investigation, Writing – review & editing. **Aoibheann Gaughran:** Conceptualization, Investigation, Writing – review & editing. **Caroline McKeon:** Conceptualization, Investigation, Writing – review & editing, Visualization. **Catherine Farrell:** Conceptualization, Investigation, Writing – review & editing. **Cian White:** Conceptualization, Investigation, Writing – review & editing. **Ian Donohue:** Conceptualization, Investigation, Writing – review & editing, Funding acquisition. **Jane Stout:** Conceptualization, Investigation, Writing – review & editing, Funding acquisition. **Yvonne M. Buckley:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Data availability

No data was used for the research described in the article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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