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Identifying key ecological components to describe the condition of Sphagnum Bogs and Associated Fens and inform their management

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Front cover: 'Flowers blooming in a bog' by ACT Government.

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Executive Summary

Alpine Sphagnum Bogs and Associated Fens, or peatlands, are unique high altitude wetland ecosystems with specific environmental conditions that include being permanently wet, cold, acidic and low in nutrients. Peatlands store and slowly release large amounts of water, improve water quality, and sequester large quantities of atmospheric carbon. They also support a diverse range of plant and animal species, including many species that only occur in these ecosystems.

Despite being listed as an endangered community since 2009, there is currently no definition of what a ‘healthy peatland’ is. There is no consistent set of ecological components, indicators, or methods for assessing the condition of peatlands in Australia, and no target thresholds for what might be considered good or poor quality. This has two major consequences; the condition of peatlands across Australia is generally unknown, and conservation policy, monitoring and management decisions cannot be carried out effectively.

The purpose of this report is to identify and prioritise a consistent or common set of key ecological components that can be used to assess baseline condition, trends in condition, and inform the management of peatlands in Australia.

We reviewed the literature to identify commonly recognised biological and physical characteristics that are core conservation values of peatlands and key properties for healthy ecosystem functioning. Seven broad ecological values were identified, including hydrology, vegetation, peat, native fauna, chemistry and nutrients, peatland extent and carbon storage. We also identified the ecosystem stressors in peatlands which were commonly associated with reduced condition of one or more ecological values. Ten broad stressors were identified, including climate change, fire, invasive hard-hooved animals, invasive predators, other invasive fauna, weeds, pathogens and disease, recreation, infrastructure and development, and resource use.

This report develops a conceptual model for peatlands which classifies the key ecological components and identifies the causal relationships among them based on the literature. This model can be used to understand what drives changes in these core ecological values, and what types of impacts different stressors have on peatlands.

For each of the 17 ecological values and stressors, we reviewed (1) why they are considered key ecosystem components, (2) how they are most likely linked with threatening processes, (3) what management actions are possible, (4) the current level of understanding or evidence around their impacts, and (5) what indicators could potentially be measured in the field to reflect their condition. This information can be used to determine how best to research and monitor each component. We also outline what management actions are available for each to improve their condition or reduce the impacts of stressors. Finally, each key ecosystem component was prioritised within the ecosystem model based on their importance to the health and condition of peatlands.

This report is the first in Australia to identify a common set of peatland components for assessing ecosystem condition. It can be used as a framework to help guide condition assessments, develop long-term research and monitoring projects, inform management actions and assess their success, and identify knowledge gaps for Alpine Sphagnum Bogs and Associated Fens in Australia.

Introduction

Alpine Sphagnum Bogs and Associated Fens (henceforth termed peatlands) are unique wetland ecosystems that have a peat substratum made of partially decomposed organic matter. They are permanently waterlogged with the water table at or near the surface, have low nutrients and acidic soils and occur in high altitude areas with low temperatures like gullies or depressions (DEWHA 2008, Hope et al. 2009, ACT Government 2017a). These specific environmental conditions result in a unique and specialised composition of flora and fauna that depend on them (Department of the Environment 2015). They intercept, filter and store large volumes of water, slowly releasing high quality water downstream (Hope et al. 2009, Silvester 2009, Department of the Environment 2015). Peatlands store and preserve large amounts of atmospheric carbon, and so are important for reducing greenhouse gases (Joosten 2010, Hope and Nanson 2015, Leifeld and Menichetti 2018). Peatlands are also culturally important, with evidence of traditional Aboriginal occupation being found within peatlands and surrounding areas (ACT Heritage Council 2004). Peat soils also provide geological records of the botanical, fire and climatic histories of the region (Hope 2003).

Peatlands are subject to multiple threats, ranging from wide scale impacts like climate change and wildfires, to more localised impacts from invasive species and human activities (Rowland et al. 2023). The national Alpine Sphagnum Bogs and Associated Fens Ecological Community was listed as endangered under the Environment Protection and Biodiversity Conservation Act 1999 in January 2009 due to its small geographic distribution coupled with demonstrable threats, the continued decline of functionally important species, and the severe reduction in community integrity across its range (Threatened Species Scientific Committee 2009, ACT Government 2019).

Despite being listed as an endangered community since 2009, there is currently no definition of what a ‘healthy peatland’ is. There is no consistent set of key bog components, indicators or methods for assessing the condition of peatlands used in Australia, and no target thresholds for what might be considered good or poor quality (Department of the Environment 2015, Rowland et al. 2023). Consequently, the condition of peatlands across Australia is generally unknown. Department of the Environment (2015) state that it is therefore of the highest priority to identify and develop an agreed method for determining condition of the ecological community (considering flora, fauna and non-biotic indicators) and an acceptable baseline condition rating for an appropriate sample of patches. One of the 25 priority research questions identified for alpine peatlands by Rowland et al. (2023) is to understand “which variables are important indicators of ecosystem health, and how can the prime and poor conditions (i.e., ecosystem states) for ecohydrological function of peatlands be defined?”.

Without a consistent definition of what a ‘good condition peatland’ is, not only are we unable to determine peatland health, but conservation policy, monitoring and research also cannot be conducted effectively. For instance, specific and measurable objectives and goals for peatland health cannot yet be established. Consequently, most of the current conservation objectives for Australian peatlands in strategies and plans include broad terms like maintaining or improving condition or ecological character (Department of the Environment 2015, ACT Government 2019, 2022). Assessing the success of broadly defined conservation objectives such as these with real data is challenging and open to interpretation. Monitoring programs will only be effectively designed once indicators that reflect ecosystem condition have been identified and specific measurable goals or questions have been established.

Indicators not only need to inform ecosystem condition, but also need to link clearly with land management. This has two important consequences for the choice of indicators. Firstly, indicators need to be able to have management trigger points and inform the level of intervention needed. Without explicit management triggers for key indicators, timely interventions in peatlands that are in decline cannot occur (Rowland et al. 2023). Secondly, ecological indicators need to inform the state or condition as well as apparent impacts or pressures in peatlands. The reason why a change in peatland condition is occurring needs to be understood to properly link with management decision making. This will contribute to a better understanding of the risks of ongoing degradation and guide management responses (depending on severity and risk) that aim to reduce vulnerability, impacts, pressures and improve resilience (Wild and Magierowski 2015) Consequently, a clear set of indicators that reflect peatland condition is needed to effectively complete the adaptive management cycle through planning, monitoring, management and evaluation.

Aim and Approach

The aim of this report is to identify a consistent or common set of key ecological components that can be used to assess baseline condition, trends in condition, and inform the management of bogs and fens in Australia. To do this, we completed the first review of the literature to identify and prioritise key ecological components of bogs and fens in Australia that could be used to describe their condition and help inform their management. From that review, we developed a conceptual model which classified these key ecological components and identified the causal relationships among them. We then asked peatland experts to prioritise the key components within the ecosystem model based on their perceived importance to the health and condition of bogs and fens. Finally, we reviewed (1) why they are considered key ecosystem components, (2) how they are most likely linked with threatening processes, (3) what management actions are possible, (4) the current level of understanding or evidence around their impacts, and (5) what indicators could potentially be measured in the field to reflect their condition. This report can be used as a framework to help guide condition assessments, develop long-term research and monitoring projects, inform management actions and assess their success, and identify knowledge gaps for bogs and fens in Australia.

Identifying key components of bogs and fens

We reviewed the literature to identify a set of common components that were specifically remarked as critical for the health of bogs and fens. We found seven relevant studies, reports or reviews (listed in Table 1) that made explicit suggestions about which types of values or indicators are key for bog health.

Each study typically suggested quite specific variables that we then grouped into broad categories. For example, the broad category 'hydrology' was made up of suggested condition variables from the literature including water retention ability, table-water level, filtration, inflows and outflows and the presence of pools and streams. The seven broad value categories included: hydrology, vegetation, peat, chemistry/nutrients, peatland extent/area, fauna and carbon storage (Table 1). Hydrology was the most important value, identified by all seven studies as important to the health of bogs and fens, followed by vegetation (6/7 studies), and then peat and chemistry/nutrients (5/7 studies for both). Fauna, peatland extent/area and carbon storage were all rarely suggested as a key value (2/7 studies) and no study listed connectivity between bogs and fens as an important indicator of condition.

Table 1 Ecological values that have been suggested by various key documents as important factors contributing to the condition of bogs and fens in Australia.

Value	Wild and Magierowski (2015)	Bonnett et al. (2009)	Macdonald (2009)	Good (2006)	Department of the Environment (2015)	Rodda (2019)	Wild et al. (2010)
Hydrology	x	x	x	x	x	x	x
Vegetation	x	x		x	x	x	x
Peat	x			x	x	x	x
Chemistry/ Water quality/ Nutrient and Carbon cycling	x	x		x	x		x
Peatland Extent/Area				x	x		
Fauna					x		x
Carbon storage		x	x				

In comparison to ecological values, the key stressors or threats that impact peatlands were more consistent across the literature (Table 2). Of the 13 key stressors identified, four were recognised as having severe impacts in all studies (climate change, fire, introduced hard-hooved animals, and weeds) and all but three (domestic stock, alien fish, and European wasps) were recognised by a majority of studies (four or more). In further developing and describing these stressors in the following sections of this report, domestic stock has been grouped with invasive hard-hooved animals, while alien fish, European wasps, and rabbits/hares were grouped as “Other invasive fauna”.

Table 2 Ecological stressors listed by various key documents as important factors impacting the health of bogs and fens in Australia.

Stressor	Department of the Environment (2015)	McMahon et al. (2015)	Rowland et al. (2023)	ACT Government (2017)	ACT Government (2022)	DEWHA (2008)	ACT Government (2019)
Climate Change	x	x	x	x	x	x	x

Stressor	Department of the Environment (2015)	McMahon et al. (2015)	Rowland et al. (2023)	ACT Government (2017)	ACT Government (2022)	DEWHA (2008)	ACT Government (2019)
Fire	x	x	x	x	x	x	x
Invasive hard-hooved animals	x	x	x	x	x	x	x
Weeds	x	x	x	x	x	x	x
Invasive predators	x	x	x	x	x		
Recreation	x	x	x	x		x	x
Rabbits/hares	x	x		x	x		
Pathogens and diseases	x	x	x	x	x		
Infrastructure and Development	x	x	x	x		x	
Resource use	x	x	x			x	
Domestic stock	x	x					
Alien fish	x	x					
European wasps				x	x		

Conceptual Ecosystem Model

We developed a peatlands ecosystem conceptual model that explicitly classifies the key peatland components and identified the causal relationships among them (depicted as arrows; Figure 1). To do this, we conducted detailed reviews of each of the ecological values and stressors identified above from the literature. For each of the values, we reviewed why they were considered key ecosystem components and their main drivers of change. For the ecological stressors we reviewed the threatening processes they drive and their impacts on values. We also investigated management options associated with the values and stressors. The key components in the model were therefore distinguished into five different categories based on their roles within the ecosystem, they include:

1. **Ecological values**. These are the biological and physical environmental characteristics that have been identified as core values for conservation and key for healthy ecosystem function. Seven ecological values were categorised, including hydrology, vegetation, peat, native fauna, chemistry and nutrients, peatland extent and carbon storage.
2. **Primary drivers**. These are the natural ecological drivers or historical processes that determine the distribution, composition, and structure of ecosystems. Primary drivers are factors that should be taken into account when determining the change in condition over time as they can explain the context of sites and why they may differ in terms of management effectiveness. In many cases they are the processes maintaining ecosystems in their natural states. Primary drivers include: topography, grazing history, past land use, fire history, climate and geology.

3. **Ecological stressors**. These are either a novel component in the ecosystem (e.g. introduced species) or an ecological value or primary driver that is beyond its normal range of variation that elicits a change in the condition of ecological values via one or more threatening processes. Hence, ecological stressors are at the start of a causal chain of events that leads to reduced condition of one or more ecological values. Ten stressors were categorised, including climate change, fire, invasive hard-hooved animals, invasive predators, other invasive fauna, weeds, pathogens and disease, recreation, infrastructure and development, and resource use.
4. **Threatening processes**. These are the mechanisms or processes through which one or more ecological stressor may reduce the condition of ecological values. A decline in the condition of an ecological value may be a result of negative impacts to its function, survival, fitness, health, behaviour, life history, evolutionary development, or distribution. Hence, threatening processes may impact ecosystems at a regional (e.g. novel climates) or site scale (e.g. weeds). The threatening processes identified include: 'reduced snow cover', 'reduced streamflow, water table and water availability', 'peat drying, decomposition or hydrophobic soils', 'erosion and channelling', 'streambank damage', 'altered drainage and runoff', 'sedimentation and turbidity', 'bare/exposed peat or damaged surfaces', 'trampling, wallowing and peat compaction', 'weed and pathogen spreading', 'browsing and selective grazing', 'competition or predation', 'stress and/or direct mortality', '*Sphagnum* bleaching', 'altered growth and productivity', vegetation type shifts and habitat modification', 'pollution (faeces, rubbish, nutrients)'.
5. **Management actions**. These most often aim to eliminate or reduce the impact of ecological stressors and threatening processes on ecological values, but can also aim to enhance values directly through restoration actions (e.g. planting). Management actions include: vertebrate pest management, weed management, fire management, enhancement and restoration programs, biosecurity protocols, visitor management and education, and policy and planning.

The bogs and fens conceptual model (Figure **1**) identifies causal impact chains from ecological stressors through to ecological values. For example, the stressor 'invasive hard-hooved animals' is the start of a causal chain, driving the threatening process of 'erosion and channelling', which in turn impacts the ecological values hydrology, vegetation composition and structure, peat substratum and carbon storage. Management actions that seek to disrupt this chain include vertebrate pest management and enhancement and restoration projects. For simplicity, causal linkages among stressors (e.g. fire leads to increased weeds), threatening processes (e.g. predation leads to stress and/or direct mortality of vegetation/fauna), and values (e.g. functioning hydrology leads to healthier vegetation structure and composition) have not been considered in this model.

For simplicity, causal linkages among stressors (e.g. fire leads to increased weeds), threatening processes (e.g. predation leads to stress and/or direct mortality of vegetation/fauna), and values (e.g. functioning hydrology leads to healthier vegetation structure and composition) have not been considered in this initial model. However, future iterations should consider such interactions as we learn more.

Finally, the model was reviewed by an expert reference group of six experts from across Australia.

This model provides a framework for undertaking ecosystem condition assessments and making qualified inference of the likely causal factors of condition. All components and causal relationships in this model are described in detail in the *Review of Key Bog and Fen Components* section below. The full model contains a lot of information and pathways so it can be hard to extract specific information around certain components, as such much of its value comes from exploring subsets of this model around specific components of interest. Therefore, we have provided subsets of the full model for each of the ecological values and stressors in the sections below for extra clarity.

Figure 1 *The Conceptual model for the bogs and fens in Australia. Ecological stressors can cause multiple threatening processes, which in turn can impact ecological values, and therefore the health and condition of peatlands. Causal linkages are indicated by the arrows, where the different colours are only used to help distinguish among different components. The choices of ecosystem components and the linkages between each of the different properties (i.e. stressors to threatening processes to values) are outlined in the following sections. Primary drivers create the context for the condition of peatlands and can influence the strength of effects from stressors and threatening processes. Those management actions that focus on eliminating stressors to improve peatland condition are labelled on the corresponding stressors in grey circles, while those that aim to enhance ecological values (rather than remove a stressor or threatening process) are labelled on the corresponding values.*

Review of Key Bog and Fen Components

This section provides detailed reviews of each of the ecological values and stressors from the literature. For each of the values, we reviewed why they were considered key ecosystem components and their main drivers of change. For the ecological stressors we reviewed the threatening processes they drive and their impacts on values. We also discuss potential management options and indicators that could potentially be measured in the field to reflect the condition of the values and stressors.

Ecological Values

Hydrology

Hydrological processes are fundamental to the existence and restoration of bogs and fens in Australia (Bonnett et al. 2009). Groundwater availability and an impeded drainage system that keeps the water table at or near the surface is critical for bog formation (Department of the Environment 2009). Changes in water table depth or water availability drive changes in species composition and diversity, decomposition, microbial activity, nutrient availability and cycling, stream water quality, flooding and greenhouse gas emissions (Gutierrez Pacheco et al. 2021). It is thought that water table depth drives primary production and surface vegetation growth, mainly for *Sphagnum* (Gutierrez Pacheco et al. 2021). However, McMahon et al. (2015) suggests that the roles of groundwater and surface water as drivers of peatland formation and function are currently only inferred and that research is required to better understand their roles. As the climate changes, the role of hydrology in bog and fen functioning will arguably be the most important attributes to understand. Nonetheless, functional hydrology is likely to be critically important for the growth and health of vegetation including *Sphagnum*, to enable the continued formation of peat soils, and to prevent encroachment by dry-land species (Department of the Environment 2015, ACT Government 2017).

Drivers of change in hydrology

Hydrology can be impacted by 7/10 stressors and 10/17 threatening processes (Figure 2). For instance, damage to bogs can lead to erosion and channelling which can result in reduced or destroyed water holding capacity (Department of the Environment 2015). Bogs in Australia rely on groundwater baseflows and are sensitive to changes in groundwater flows or discharge that can occur from damaging activities (e.g. fire, peat excavation) (Bonnett et al. 2009). Factors that could be underlying any changes in hydrology include: increased erosion and channelling, trenching and flow redirection, altered drainage, hydrophobic soils, amount of bare and exposed peat, previous fire impacts, trampling or peat compaction, presence and total area of wallows, shifts in vegetation (particularly *Sphagnum* moss which has a large water holding capacity), presence or abundance of certain weeds, or changes in precipitation and subsequent effects on groundwater recharge, temperature, evapotranspiration or snow cover with climate change. It is important to understand *why* changes in hydrology may be occurring to properly manage their recovery.

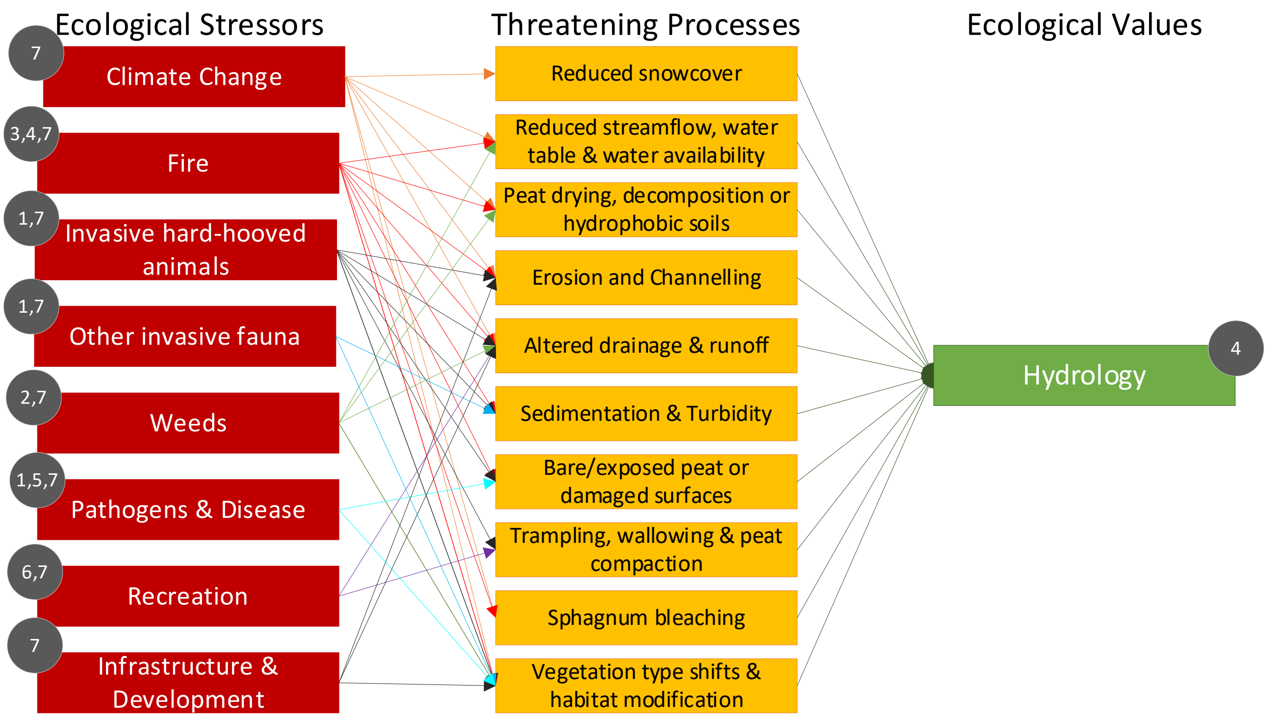

Figure 2 *Subsection of the conceptual model for the bogs and fens focusing on the stressors and threatening processes that are causally linked to hydrology specifically. The numbers in the grey circles represent potential management actions, they include (1) vertebrate pest management, (2) weed management, (3) fire management, (4) enhancement and restoration programs, (5) biosecurity protocols, (6) visitor management and education, and (7) policy and planning.*

Potential management actions for hydrology

Clarkson et al. (2017) suggests that in bogs and fens that have lost their hydrological function, the rehydration of dry and exposed peats by raising water tables, retaining water, and slowing surface and subsurface flows are priority restoration actions for reinstating proper hydrological functioning. There are several techniques available for restoring hydrological functions, including water-spreading (e.g. coir logs to slow and outspread flows, trap sediment, and promote rewetting of desiccated peats), creating pools, controlling flows and creating subsurface dams (Clarkson et al. 2017). Rowland et al. (2021) identified three interventions that aimed to restore and maintain hydrological conditions, including rewetting, shading or mulching, and cutting vegetation. Rewetting involves blocking drainage points to allow water to accumulate and/or watering to re-saturate and restore waterlogged soils that have been drained. Interventions to increase water flowing into peatlands (e.g. removing blockages preventing water into the system such as roads, or adding water) also improved hydrological conditions. Shading or mulching aims to prevent desiccation of peatland surfaces and vegetation and can potentially reduce hydrologic impacts when used alongside other interventions such as reprofiling surfaces, rewetting and planting. Cutting and removing trees has also been reported to increase the water table in managed peatlands. Good (2006) suggests that bogs which become hydrophobic (for instance after fire) are likely beyond rehabilitation.

Potential Indicators of hydrological condition

When water holding capacity and the water table are functioning correctly, the water table fluctuates seasonally and diurnally, although deeper peat is permanently waterlogged (Wild and Magierowski 2015, ACT Government 2017, Gunawardhana et al. 2021). Changes in water table depth are associated with water availability and storage (Gutierrez Pacheco et al. 2021), such that fluctuations in water levels reflect the overall water balance of the site (Bonnett et al. 2009).The seasonal changes in amplitude of water table height are key indicators that the system is healthy. Seasonal fluctuations in water table depth are likely normal in healthy peatlands, reflecting seasonal changes in groundwater delivery, precipitation and water loss. These water table depth changes will impact on microbiological processes and the chemical regulation processes in the peatland (Ewen Silvester, pers. comm., 2020). When the system is not functioning properly, the water table will fluctuate within mineral soils or can be constrained by ditches and drains and deeper peat might dry under drier conditions (Wild and Magierowski 2015).

In terms of moisture, *Sphagnum* layers should be well saturated and pools should be present under non-drought conditions (Wild and Magierowski 2015). When a bog or fens moisture status is in poor condition, evidence of desiccation on bog edges and within bogs may be found, ‘dryland’ plant species may begin to invade the site and some pools or water channels may dry.

Measuring the hydrology of bogs and fens can include a range of different hydrological aspects and variables. Many of the suggested variables from the literature focus on water balance, including the magnitude, duration and seasonality of: water retention/storage/holding ability and capacity, water table level, seasonal changes in amplitude of water table height, filtration, water release rates, stream flow velocity, inflows and outflows through catotelm (the lower layer of peat which is constantly saturated, has no air entry and is microbe-poor) and acrotelm (the surface layer of peat which contains an oscillating water table with variable water content and is subject to periodic air entry). While other suggested factors focus on moisture availability, including: moisture status of peat and *Sphagnum*, or the presence of pools and streams (Good 2006, Bonnett et al. 2009, Macdonald 2009, Wild et al. 2010, Department of the Environment 2015, Wild and Magierowski 2015, Rodda 2019). Additionally, proxies that indicate poor hydrological functioning in a bog and fen can include desiccation on bog edges, shift in species composition favouring dryland species and the presence/abundance of trees.

Bonnett et al. (2009) states that to fully understand the hydrology of a site, several different hydrological parameters should be monitored so that the water balance can be established, including precipitation, evapotranspiration, groundwater inflow and outflow, surface water inflow and outflow and water storage. Yet they acknowledge that in practice such detailed monitoring is unlikely, and that whatever parameters are chosen should be able to answer the questions driving the project or restoration.

Vegetation

Vegetation is a key structural, compositional, and functional component of bogs and fens. Vegetation structure and composition are suitable indicators to characterise the state of bogs and would generally show a response to changes in state in the medium term of 5-10 years (Wild and Magierowski 2015). Vegetation is not only a visually distinctive aspect of the community, but also a key component to the proper functioning of bogs and fens, influencing rates of evapotranspiration and peat deposition, erosion and providing habitat for species. Most of the literature focuses on vegetation condition for *Sphagnum* bogs, rather than fens or other bogs.

For *Sphagnum* bogs, *Sphagnum* moss is considered the most important aspect of vegetation. *Sphagnum* plants are considered to be amongst the principal peat formers by mass (Clymo 1970). *Sphagnum* is also a key species used to define the habitat. Its morphology, anatomy, physiology and composition make it an effective ecosystem engineer (van Breemen 1995). Not only do *Sphagnum* mounds provide much of the key structure to bog communities (Bonnett et al. 2009), *Sphagnum* also maintains a very acidic pH level (range 3.5-4.5) that limits the range of taxa that can survive in the ecological community (van Breemen 1995, Hope et al. 2012). Like peat, *Sphagnum* has a significant water holding capacity, which may be important in modulating water flow and maintaining the hydrology of surrounding vegetation (Department of the Environment 2015). Intact stands of *Sphagnum* also act as a natural filter for nutrients, pathogens and sediments, thus playing an important role in maintaining downstream water quality (Threatened Species Scientific Committee 2009).

Drivers of change in vegetation

Vegetation can be impacted by all 10 stressors and 15/17 threatening processes (Figure 3). For instance, increased temperatures and UV radiation from climate change will likely decrease plant growth, increase *Sphagnum* bleaching and contribute to shifts in species composition. However, higher carbon dioxide levels from climate change will likely increase plant growth (Hope and Nanson 2015, ACT Government 2017). Decreased water availability can lead to loss of *Sphagnum* (Whinam and Chilcott 2002, Hope et al. 2009). Fire can also cause large and immediate changes to the structure and species composition depending on the fire-sensitivity of different species (McMahon et al. 2015). Peat soil fires can kill roots and propagules and physically remove the soil substrate needed for plants to grow (Prior et al. 2020).

Trampling, browsing and grazing by hard-hooved animals (and potentially humans) can impact the vegetation community via vegetation damage/removal, facilitating exotic weed invasion, and driving shifts to other vegetation types (Pellerin et al. 2006, Department of the Environment 2009, Rowland et al. 2023) and cause stream channel damage. Rabbits can reduce the cover and diversity of forb species in these areas, and can change the structure and composition of the habitat (McMahon et al. 2015). Both woody and non-woody weeds compete with native species for space, water and nutrients and can irreversibly change the floristic composition, structure and hydrology (Department of the Environment 2009, McMahon et al. 2015). The composition and structure of the vegetation community can be impacted by particularly damaging species such as certain *Juncus* spp. and willows (*Salix* spp.) (Department of the Environment 2015). Finally, fungal pathogens, such as *Phytophthora* are considered likely to emerge in bog and fen communities and can be damaging to species that are susceptible to them, such as common peatland shrub species from the genus' *Epacris* and *Richea* (McMahon et al. 2015).

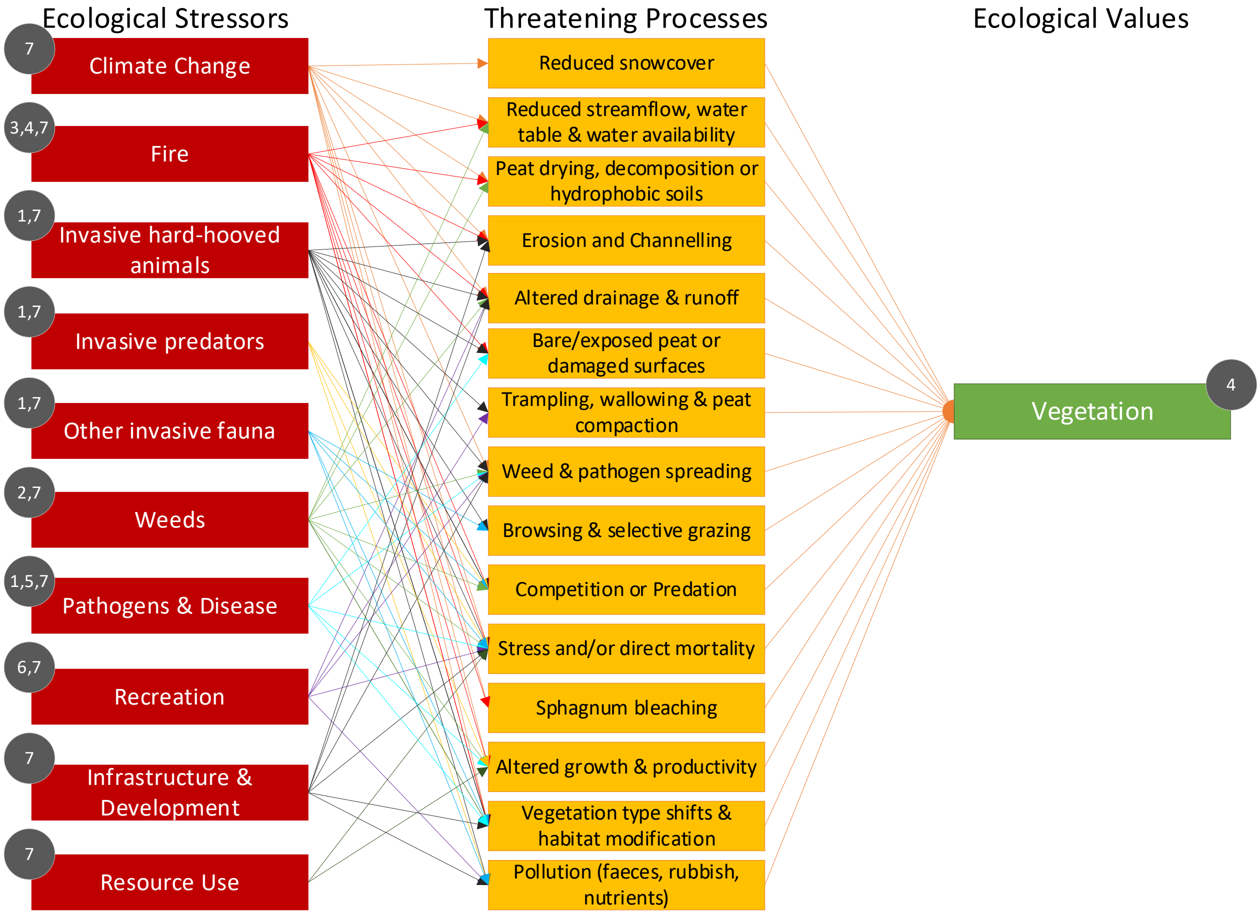

Figure 3 *Subsection of the conceptual model for the bogs and fens focusing on the stressors and threatening processes that are causally linked to vegetation specifically.*

Potential management actions for vegetation

Re-establishing vegetation is key to restoring degraded peatlands. Revegetation can occur actively via management intervention or passively via natural recruitment and succession processes. Active revegetation can include spreading herb seeds, directly planting herb or shrub seedlings and spreading mosses or moss fragments. These techniques are generally considered to be effective at restoring or increasing vegetation, but often need other simultaneous interventions such as rewetting, reprofiling or fertilising (Rowland et al. 2021). Leaky weirs aim to slow water in the system and spread it throughout the peat, with the intention of improving the health and growth of vegetation that might be encountering the unfavourable conditions of drying soils or lowering water tables. One common short-term technique to improve the survival and growth of *Sphagnum* after fires is the use of shade cloth (Macdonald and McLean 2023).

It is critical to understand *why* the vegetation is changing so that decisions can be made around what management actions should be employed, and at what point they should be implemented. For instance, shifts in vegetation due to changes in the rate of evapotranspiration versus impacts of invasive species would need substantially different management responses if management was deemed necessary.

Potential indicators of vegetation condition

For the national description of Alpine *Sphagnum* Bogs and Associated Fens Ecological Community, vegetation that is in good condition consists of a natural to semi-natural vegetation cover including *Sphagnum*, rushes, sedges and a diversity of Ericaceous and Myrtaceous shrubs. When in poor condition, there could be reduced, little or no presence of key species such as peat forming *Sphagnum*, rushes and sedges and depauperate level of other species (Wild and Magierowski 2015).

Several studies have measured species richness in peatlands across Australia (Whinam et al. 2003a, Whinam et al. 2010, Rodda 2019), but it is currently unclear whether simply the number of species present reflects the overall health of the site. Species richness can vary with altitude, rather than the health of a site (Hope 2006). Consequently, species richness may not be a viable indicator of condition. As a result, focusing on key species, or breaking up cover into functional groups may be more suitable and can be more easily interpreted. For instance, the post-fire research investigating the success of coir logs in vegetation recovery distinguishes the percentage of cover of several distinct vegetation categories (Macdonald and McLean 2023). These include: *Sphagnum* moss (live, bleached or dead), other mosses, herbs, *Empodisma minus*, grass, sedge or rush, woody perennials (live or dead) and any overstorey cover. In addition to these vegetation types, they also record the percent cover of bare ground, litter, rock and pools. The abundance and cover of certain key species might also be recorded, for instance, *S. cristatum, E. minus* (which contributes significantly to peat formation)*, Carex gaudichaudiana (*typically dominating fens), and *Poa costiniana* which occurs on the margins of bogs and tends to invade degraded sites (Hope 2006, Hope et al. 2012, Department of the Environment 2015). *C. gaudichaudiana* are a grass-like sedge that is scattered in bogs but forms, and then dominates fens. *Carex* forms an effective filter and spreads water out across valley floors. *Poa* tussock grasses are commonly scattered in bogs but will invade if they dry out, and so can be an indicator of degrading peatlands (Hope et al. 2012).

Sphagnum is a good indicator species of the health of *Sphagnum* bog communities (Growcock and Wright 2007, Bonnett et al. 2009). *Sphagnum* cover, for instance, can be considered an important parameter which indicates the proper functioning of a peatland. The presence of *Sphagnum* indicates functional water table depths and hydrological regimes (Bonnett et al. 2009). Indeed, growth rates of moss have been found to vary according to the availability of free surface water (Growcock and Wright 2007). The total area of *Sphagnum* at a site can prove difficult, if not impossible, to measure because of its location hidden underneath other vegetation types. Consequently, opportunities to measure changes in total *Sphagnum* extent/area are possible after wildfires as they are fully exposed.

A number of orchid species which are listed nationally as critically endangered occur in bogs and fens in Australia (although are not restricted solely to peatlands), including the Kiandra Greenhood (*Pterostylis oreophila*), Bago Leek Orchid (*Prasophyllum bagoensis*), Brandy Mary's Leek Orchid (*Prasophyllum innubum*) and Kelton's Leek Orchid (*Prasophyllum keltonii*) (Department of the Environment 2015).

Peat

The presence of a peat substratum is a defining component of the Nationally described bog and fen ecological community (DEWHA 2008, ACT Government 2020). Peat is an organic soil that develops when plant material does not decompose completely due to specific environmental conditions. The formation of peat requires cool, acidic, anaerobic and permanently waterlogged conditions (Grover et al. 2012, Department of the Environment 2015). Bogs and fens will only continue to accumulate peat if plant material build up exceeds losses due to decay and removal. Peatlands in the Snowy Mountains cover nearly 8000 ha and preserve 49 million m^3 of peat, of which 27.1 million m^3 is stored in *Sphagnum* shrublands and restiad moorlands, and 21.9 million m^3 is stored in sedge fens (Hope and Nanson 2015). Hope et al. (2009) suggests that over the past few millennia the ACT peatlands reflect a very slight positive balance, with long-term accumulation rates in the order of 0.01-1.0mm per year.

Drivers of change in peat substrate

Peat soils can be impacted by all 10 stressors and 11/17 threatening processes (Figure 4). Extensive areas of peatlands across Australia's alpine and subalpine regions no longer have active peat accumulation (Department of the Environment 2015). Erosion, gullying and fire are three major contributors to declining peat growth (Macdonald 2009). Without permanent waterlogging, the loss of anaerobic conditions, more pH neutral conditions can all contribute to decreased peat formation (Department of the Environment 2015). Stressors such as drought and fire will likely decrease organic matter available to become peat (Hope 2006). Once the rate of peat loss or decay increases and peat drying at the surface occurs, further peat development might be completely prevented (Macdonald 2009). It is currently unclear whether current environmental change (e.g. climate change, fire) will alter the formation or stabilisation of peat (Bonnett et al. 2009).

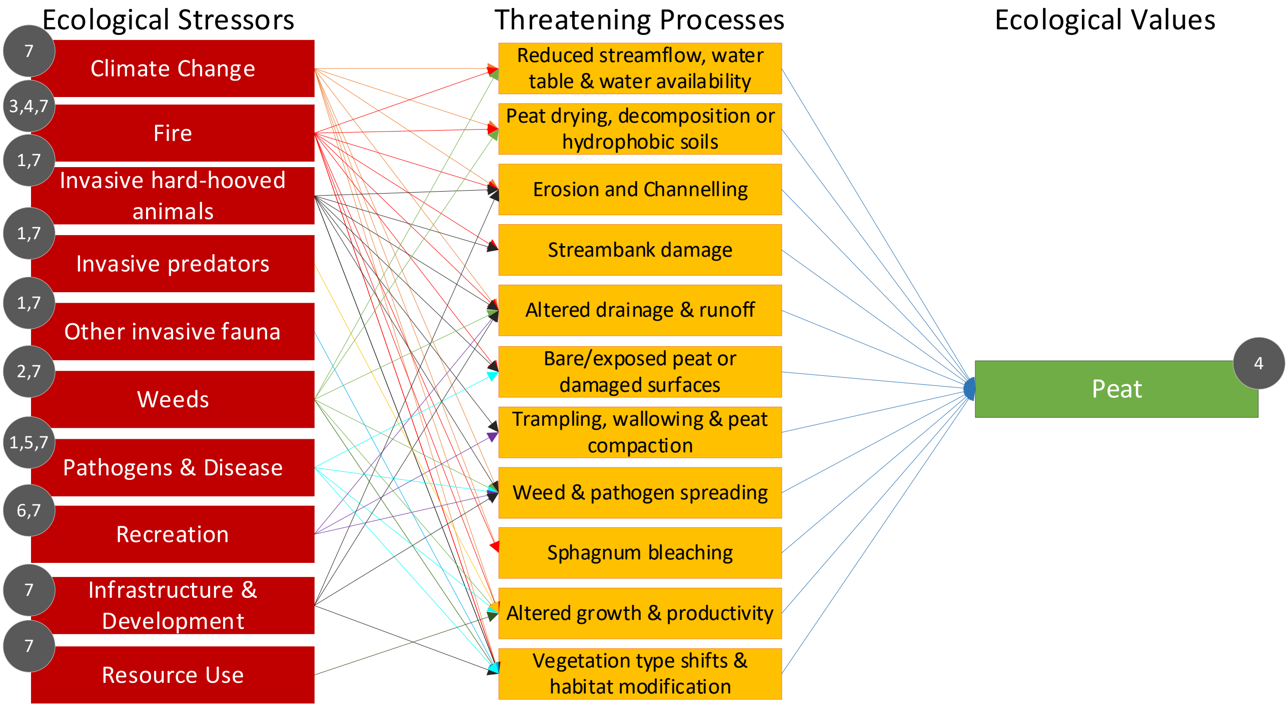

Figure 4 *Subsection of the conceptual model for the bogs and fens focusing on the stressors and threatening processes that are causally linked to peat soils specifically.*

Potential management actions for peat

Management actions that aim to slow and spread water throughout peat are used to assist with peat rehydration, reduce erosion and prevent soils from becoming hydrophobic (Good et al. 2010, Clarkson et al. 2017). Parry et al. (2014) present a number of common management actions for restoring peat after impacts have occurred, including drain blocking techniques, gully blocking and reprofiling to reduce gully side slope steepness to reduce erosion rates, and stabilising bare peat by re-establishing vegetation (by seeding or pre-grown seedlings), mulching or spreading natural fibres or textiles (e.g. heather brash textiles or geo-jute).

Potential indicators of peat condition

Peat substrates that are healthy are considered to have intact acrotelm (surface peat layer) and catotelm (lower saturated peat layer) layers and little to no evidence of peat oxidation. Organic matter should be actively fixed and stored in the acrotelm and have potential for long-term storage in the catotelm (Wild and Magierowski 2015). When the system is not functioning properly, little organic matter will be incorporated into alpine humus soils or waterlogged layers and plant litter may degrade at the surface and/or not enter system as peat. There may be areas of wasted or lost peat with no true organic matter layer, and evidence of peat oxidation and subsequent erosion (Wild and Magierowski 2015). Indicators of poor condition peat substrate can include the presence of tunnels or peat collapse, evidence of upper layer of peat no longer intact (e.g. erosion present) or hydrophobic surface layers (Good 2006, Wild and Magierowski 2015).

Measurements of peat integrity include the condition of the peat mass and of the peat material. Parameters indicating the condition of the peat mass include the degree of erosion present, and the degree to which the peat mass is dissected by grips. Parameters used to indicate the condition of the peat material include bulk density, humification, mineral content, compaction (drumminess), and hydrophobicity (Bonnett et al. 2009).

Peat layers in good condition bogs generally do not grow by more than 5 cm /century, while sedge (*Carex*) fens can accumulate 10 cm/century (Clark 1980). Peat accumulation is one measure of a healthy, active bog. Peat accumulation technically occurs when material is passed from the acrotelm to the catotelm (and the quantity is not exceeded by losses in the catotelm as a whole). Despite measurement of peat accumulation over long time periods being relatively easy because peat thickness can be measured and dated, measuring current rates of accumulation is extremely difficult for many reasons. For instance, the boundary between the acrotelm and catotelm is indistinct, material in the acrotelm has an unknown residence-time which can be influenced by a range of factors (e.g. presence of compounds which immobilise microbial decomposers produced by *Sphagnum*, differences in microtopography) and because the rate of decay in the acrotelm will change in response to damage and changes in climate (Lindsay 2010).

Wild and Magierowski (2015) and Wild (2011) suggest that peat depth would be a suitable measure to characterise the state of bogs and would show a response in the medium term (5-10 years). Both Whinam and Chilcott (2002) and Rodda (2019) measure substrate depth in their surveys. Accurate peat depth measurements can form the basis of long-term estimates of peat loss and subsidence, or long-term rates of accumulation (Bonnett et al. 2009). However, peat depth may not be appropriate for measuring long-term rates of accumulation as they are not going to change on these timescales (Ewen Silvester, pers. comm., 2021).

Another possible indicator of peat condition is the presence of living vegetation which is recognised as normally being associated with peat-forming conditions (see vegetation section above). This is part of the description of an 'active' peat bog under the terms of the EU Habitats Directive (Lindsay 2010). However, this indicator does not necessarily indicate if peat is actually forming at any specific instant in time. The presence of such vegetation only allows for the conclusion that the peatland area is either currently accumulating peat or at least has the capability to do so even if it is not doing so at present. Additionally, above ground biomass is not the only contributor, with almost 90% of the living biomass in fens existing below ground (predominantly in the form of fine roots) (Lindsay 2010).

Erosion pins can be used to track the degree of erosion or sediment build up with the use of leaky weirs to help restore wetlands after fire (Bonnett et al. 2009, Macdonald and McLean 2023). These give some indication of changes in peat sediment heights in response to events such as fire.

Hope and Nanson (2015) suggest that more intensive stratigraphy, dating, bulk density and carbon content data are needed to validate estimates for peat growth. Grover et al. (2005) state that standard chemical properties of peat include pH, loss on ignition, gravimetric contents of carbon and nitrogen and electrical conductivity.

Native Fauna

Native fauna are a key part of the peatland community. For instance, the conservation advice for the Australian Capital Territory (ACT) listing of High Country Bogs and Associated Fens Ecological Community specifically states that one of the reasons that the community is significant is because they provide significant habitat for endemic and threatened animal species, including the Critically Endangered Northern Corroboree Frog (*Pseudophryne pengilleyi*), the Broad-toothed Rat (*Mastacomys fuscus mordicus*) and Verreaux's Alpine Tree Frog (*Litoria verreauxii alpina*) which are protected under the EPBC Act (ACT Government 2019) and the *ACT Nature Conservation Act 2014* . The Conservation Advice for the nationally endangered community suggests that the top research priority is to design and implement long-term monitoring programs to determine condition and trends for fauna, particularly any impacts on aquatic fauna (DEWHA 2008).

Drivers of change in native fauna

Native fauna can be impacted by all 10 stressors and 12/17 threatening processes (Figure 5). For instance, fire results in an immediate loss of habitat (DEWHA 2009), and can cause long-term habitat degradation that can lead to declines in native fauna (McMahon et al. 2015). Stressors that result in modified habitats and food resources (e.g. fire, weeds, invasive species), changes in nutrients or the physical environment will all impact fauna that rely on bogs and fens. Invasive animals can impact native fauna through predation and competition, but also incidental consumption, trampling and interference (Foster and Scheele 2019). Specifically, they can disturb Northern Corroboree Frog breeding pools, egg nests and non-breeding habitat (ACT Government 2017, Foster and Scheele 2019). Aquatic fauna are susceptible to streambed and water quality changes caused by stressors such as hard-hooved animals and fire (Robertson et al. 2019). Additionally, some weed invasions (e.g. Blackberry or willows) could alter important frog-breeding habitat, impact in-stream fauna through changes to nutrient inputs or generally degrade important fauna habitat (McMahon et al. 2015, ACT Government 2017). Pathogens and diseases can also heavily impact faunal communities. For instance, Chytrid fungus has already resulted in drastic declines of the Northern Corroboree Frog and is known to impact other species such as the Alpine Tree Frog (Hunter et al. 2010, Department of the Environment 2015). Other viruses (such as the Epizootic Haematopoietic Necrosis Virus) can cause mortality in threatened fish species (ACT Government 2017).

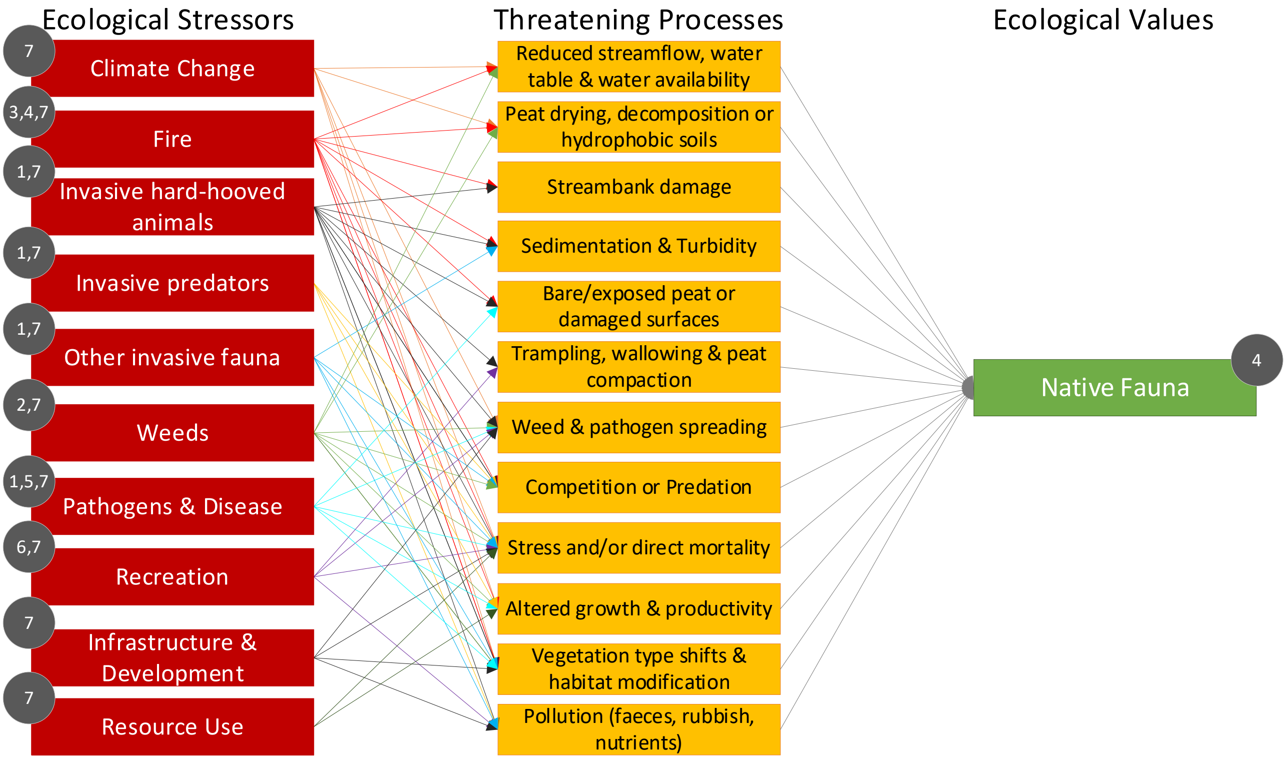

Figure 5 Subsection of the conceptual model for the bogs and fens focusing on the stressors and threatening processes that are causally linked to native fauna specifically.

Potential management actions for native fauna

The ACT High Country Bogs and Associated Fens Endangered Ecological Community Draft Action Plan (ACT Government 2022) contains suggested actions to ensure local extinctions do not occur, and describes site-specific management actions to improve the required habitat for threatened and significant species in their bogs and fens. Direct management actions to promote the health and abundance of fauna are few. The main method for managing the Corroboree Frogs is through captive breeding and release programs. However, for most other species, managing the stressors and risks that directly impact them or ensuring the persistence of high-quality habitat are the main management actions. For instance, the management actions suggested by Milner et al. (2016) to support Broad-toothed Rats in bogs and fens involved managing the effects of climate change, fire, invasive predators, invasive species that directly compete (e.g. rabbits), and weeds. Similarly, Foster and Scheele (2019) suggest that ensuring the persistence of high-quality habitat is crucial for the conservation of the Northern Corroboree Frog, particularly around the impacts of feral species on key habitat for the species.

There is very little known about how to manage many species that are important components of bogs and fens, particularly groups such as invertebrates. Workshops held in the UK suggested that maintaining or enhancing populations of invertebrates might also be objectives of a peatland restoration project (Bonnett et al. 2009). Clarkson et al. (2017) state that the recovery of invertebrate communities can be improved by focusing on restoring areas of habitat loss and reconnecting isolated patches.

Potential indicators of native fauna condition

The use of fauna as potential indicators of the health of bogs and fens has been less discussed in the literature. More research is needed to understand which species might act as useful indicators and bog and fen health. However, Bonnett et al. (2009) suggest that changes in peatlands can be assessed by monitoring the species status of those that inhabit them.

There are several potential indicator species or groups that are responsive to changes in habitat quality. The breeding habitat of frogs, for instance, could be impacted by changes in stream flow and groundwater levels (ACT Government 2017). The presence and abundance of sensitive species like Northern Corroboree Frogs can indicate a healthy system. Their declines have predominantly been found to be due to the presence of Chytrid Fungus in these communities (Hunter et al. 2010). However, other factors such as hard-hooved animals can potentially disturb Northern Corroboree Frog breeding pools, egg nests and non-breeding habitat, ultimately reducing breeding success (ACT Government 2017, Foster and Scheele 2019). Additionally, Scheele et al. (2012) found that the probability of Northern Corroboree Frog occurrence at extant sites compared with extinction sites was negatively related to tree invasion, a proxy for the underlying hydrology of the system.

Animals such as Spiny Crayfish and Broad-toothed Rats are potentially both keystone species as they contribute to the form and physical nature of the habitat through digging of burrows and forming runs throughout the site, and characteristic species as they are consistently found within the habitat. Additionally, the Broad-toothed Rat has been recognised to be impacted by predation from foxes and cats, competition from rabbits, competition and disease transmission from pigs, invasions of exotic perennial grasses, spread of the plant root fungus *Phytophthora cinnamomic* and losses in habitat from climate change (Milner et al. 2016). Montane crayfish are also known to be extensively predated upon following loss of vegetation cover from fires by foxes and birds (Lisa Evans, pers. comm., 2021).

Birds can also be used as biological indicators of environmental quality for several reasons: species are readily seen or heard and identified, some species are top of the food-chain, acting as bio-accumulators of persistent pollutants, they are important contributors to habitat quality and extent (utilising invertebrate food sources for chicks) and some are very sensitive to pollution and disturbance. Birds have broad interest to the general public meaning their use as condition indicators in a restoration project has high communication value., Bird populations also respond rapidly to many conservation management actions (Bonnett et al. 2009).

Both terrestrial and freshwater invertebrates are key components of these ecosystems. Peat provides habitat for terrestrial invertebrates such as ants, millipedes, mites, collembola, enchytraeid worms, insects and arachnids. Fens in the UK support thousands of invertebrate species, with more than half the UK's dragonfly species and large number of aquatic beetles found at some sites (Bonnett et al. 2009). Invertebrates can be an indication of the water quality or conservation value of these systems (Bonnett et al. 2009). In New Zealand, the insect fauna in bogs is known to be distinctive and plays significant roles in ecosystem processes, such as pollination, litter decomposition, and nutrient cycling (Watts et al. 2008, Clarkson et al. 2017). Invertebrates in bogs and fens are an essential component of the diet of many species, particularly birds (Bonnett et al. 2009). Scott et al. (2006) found that several species of spiders in England were an informative surrogate for the full invertebrate fauna assemblage of bogs and where therefore a good indicator of condition. Invertebrate communities are determined primarily by water chemistry and are therefore very useful for determining degrees of pollution (Bonnett et al. 2009).

Ants are considered good indicators of changes in habitat quality for large peatlands in Northern Europe (Bujan et al. 2015), but no research has been carried out in Australian bogs and fens to our knowledge. Anecdotally, ants are one of the most abundant fauna within bogs (Greg Baines, pers. comm., 2020). Outside of Australia, some ant species are known to modify peatland soil environments, influence vegetation structure and composition, change the chemistry, nutrients, moisture level, level of aeration and temperature of soils in bogs (Lesica and Kannowski 1998, Pêtal 1998). They have been found to consume and turnover higher amounts of organic matter than the input of decaying plant biomass and detritus to the soil in drained fens (Pêtal 1998). The diet of subadults and adult Corroboree Frogs consists mainly of ants and to a lesser extent other invertebrates (Pengilley 1971, ACT Government 2011).

Despite the importance of invertebrates, monitoring can be time consuming and costly as they form a large group in terms of species richness and many of them pose difficult problems for long-term monitoring. Sampling for many groups is labour intensive, identification difficult, time-consuming and therefore expensive (Bonnett et al. 2009). Ant nests can be sampled along transects (Pêtal 1998) and pitfall traps (Bujan et al. 2015).

Microorganisms perform essential ecosystem functions in peatlands particularly in respect to decomposition, water quality, mineralisation for plant productivity and greenhouse gas production in all types of peatlands. Thus, monitoring changes in microorganisms or microbial community structure and function may be important for informing condition, but also could for monitoring the success of peatland restoration. However, techniques for sampling microorganisms are expensive, time consuming and require detailed specialist knowledge as well as suitable laboratory equipment. Thus they are probably beyond the scope of most projects unless research is conducted with a university (Bonnett et al. 2009).

Chemistry and Nutrients

The proper functioning and overall health of bogs and fens is tied to their chemistry and nutrient dynamics. Seasonal changes in biogeochemical processes in bogs and fens can be used to evaluate the condition of peatlands and to inform restoration (Gunawardhana et al. 2021). Important factors could include water quality, turbidity/sedimentation, nutrient cycling/levels, pH, and pollutants. Bogs and fens are characterised by anoxic conditions that are produced by permanent inundation of peat soils, and high levels of organic acids that inhibit decomposition processes and allow peat accumulation (van Breemen 1995, Silvester 2009). Wild and Magierowski (2015) suggest that nutrient cycling ability is an important factor in determining the condition of bogs. Changes to the timing and amount of nutrient inputs (e.g. via weeds or fire) can impact in-stream fauna (McMahon et al. 2015). Australian alpine peatlands are also thought to have an important role in maintaining water quality as they act as natural filters for nutrients, pathogens and sediment, and have considerable potential to modify downstream water composition (Silvester 2009, Department of the Environment 2015).

Drivers of change in chemistry and nutrients

Chemistry and nutrients can be impacted by 9/10 stressors and 6/17 threatening processes (Figure 6). Our understanding of the chemical regulation processes that occur in intact bogs and fens and how disturbances influence these is still growing (Silvester 2009). There is currently little information available on the drivers of change in chemistry and nutrients in bogs, although microbial processes leading to nutrient regulation are very likely the same that occur in all wetlands. Nutrient and chemical regulation is seasonally variable, reflecting changes in peatland productivity and microbial environment in the peat profile (Ewen Silvester, pers. comm., 2021). Stressors such as fire can alter bog chemistry, direct deposition of urine and faeces by invasive animals can decrease water quality and alter nutrients, trampling and wallows can impact water quality by increasing water turbidity, and weeds can alter the nutrient availability for native plants (McMahon et al. 2015, Wild and Magierowski 2015, Rowland et al. 2023).

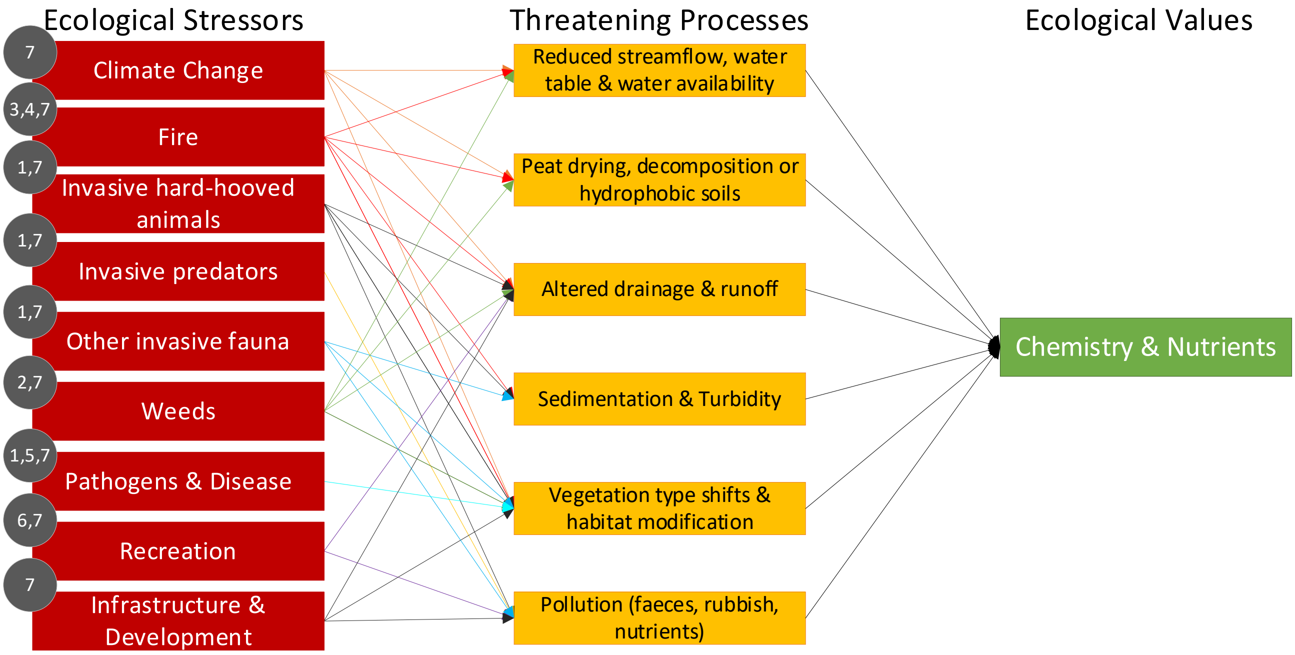

Figure 6 *Subsection of the conceptual model for the bogs and fens focusing on the stressors and threatening processes that are causally linked to chemistry, nutrients and water quality specifically.*

Potential management actions for chemistry and nutrients

Information on how to manage bog and fen ecosystems to promote proper functioning of chemical processes and nutrient cycling is currently lacking. However, Rowland et al. (2021) found that in nutrient enriched peatlands, rewetting, reprofiling, mowing and implementing new policy may improve the water and substrate chemistry.

Potential indicators of chemistry and nutrient condition

Both pH and nutrient state can be considered important indicators of a proper functioning peatland (Bonnett et al. 2009). Bonnett et al. (2009) suggest that nutrient concentrations, pH and redox potential of peat soils should be included on every monitoring protocol and monitored at least seasonally every year at different peat depths to provide important information that relates to both plant and microbial functional development on the site. Redox potential can serve as an important indicator of microbiological processes in peat as well as variation in the hydrological regime. Wild and Magierowski (2015) suggest that the chemistry (pH, ionic regulation) of peatlands is a suitable characteristic of the state of bogs and would show a response in the medium term (5-10 years). Low pH values are an indicator that anaerobic and peat forming conditions are occurring (Wild and Magierowski 2015). Peat and water chemistry measurements are also typically straight forward and relatively cheap to collect for the amount of information they provide. Water quality is likely to be a useful indicator if measured seasonally and over long time frames (Ewen Silvester, pers. comm., 2021).

Peatland Extent

Change in peatland extent or area is considered a useful indicator of the health of bogs and fens. Spatial changes in the extent of wetlands, as well as specific aspects such as open water and vegetation, can be valuable for observing the spatiotemporal behaviour of wetlands and to show the impacts of policy decisions on wetland ecosystems (Dunn et al. 2019). Reduced peatland area and increased dried peat or alpine humus soil area can cause changes in hydrology, nutrient fluxes, acidity and primary productivity in bogs (Grover et al. 2005, ACT Government 2017). The size of bogs is also an important factor for many animal species as habitat patch size determines population persistence (Banks et al. 2007). For instance, Broad-toothed Rat detection increases with bog size across bogs in the ACT (Milner et al. (2015). Generally, larger habitat patches are likely to support larger populations as well as provide a greater 'target' for individuals dispersing into the area (Milner et al. 2016).

Drivers of change in peatland extent

Peatland extent can be impacted by all 10 stressors and 6/17 threatening processes (Figure 7). Fire and climate change have been suggested to directly lead to reductions in peatland extent (Hope et al. 2009, Wild et al. 2010, ACT Government 2017), but any stressor or threatening process that leads to peat drying or shifts in peatland vegetation could all be relevant. Changes in climate, particularly temperature and rainfall can influence the extent of peatlands. Warmer conditions may encourage growth of woody species, and lower rainfall is likely to result in bog contractions and changes away from peatland vegetation communities (e.g. from *Sphagnum* bog communities to *Empodisma* fen or sod tussock communities) (Hope et al. 2009, ACT Government 2017). Fire damage can cause peatland extent to shrink via drying of peats, decomposition of peat and entrenchment of drainage lines (McMahon et al. 2015).

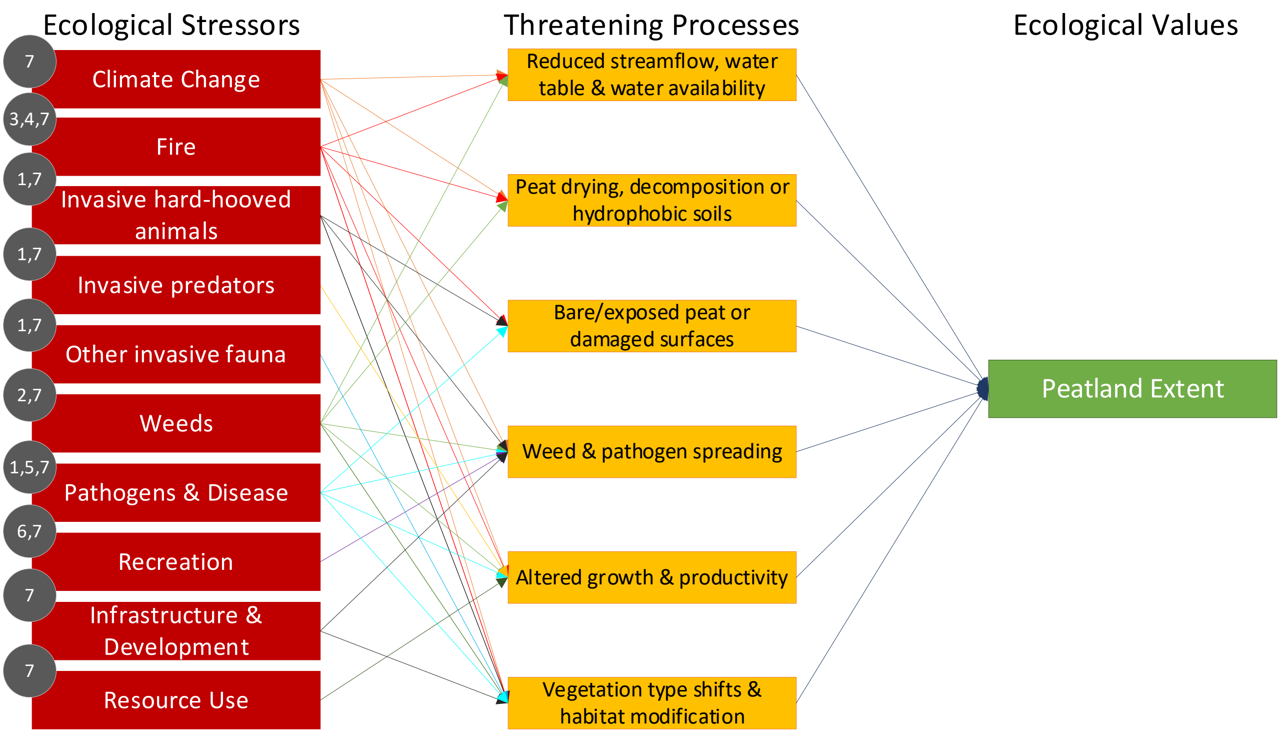

Figure 7 Subsection of the conceptual model for the bogs and fens focusing on the stressors and threatening processes that are causally linked to peatland extent or area specifically.

Potential management actions for peatland extent

Management actions that are appropriate for reducing contractions in the size of bogs and fens, or shifts in vegetation types will likely differ depending on the underlying cause. However, as drying appears to be the main underlying driver of contractions in peatland extents, management actions that slow and hold water in the system or add moisture may be key.

Potential indicators of peatland extent condition

Decreasing extent of bog and fen areas can be an indication of poor condition. McMahon et al. (2015) suggest that baseline remote sensing data can be used to determine if the extent of peatlands is increasing or decreasing over time in different clusters. Mapping against older air photo sources, maps and former peatland extent established by analysis of sediments could be used to establish the pre-European extent and historical changes in the dominant vegetation of the peatlands. Additionally, remote sensing data can provide more specific indicators of health than just the peatland area. Combining observations of open water, wet vegetation, and vegetation fractional cover allows the spatiotemporal behaviour of wetlands to be assessed (e.g. using the Wetlands Insight Tool) (Dunn et al. 2019).

While the Commonwealth Listing Advice states that the "ecological community generally has sharp boundaries and is easily delineated from other alpine vegetation communities (with) many of its plant species rarely occurring in other vegetation assemblages" (Threatened Species Scientific Committee 2009), changes in the area or extent of bogs and fens can be defined in numerous ways and it can often be challenging to determine the 'edge'. Wild (2011) developed a peatland edge decision key to help categorise peatland edges based on the presence of peatland indicator species or dryland species, substrate characteristics (e.g. organic soils present) and micro-topographical characteristics (clear break in a hill slope or groundwater upwelling).

Carbon Storage

Peatlands cover less than 3% of the earth's surface but may store 21% of the global total soil organic carbon stock (Joosten 2010, Leifeld and Menichetti 2018). Although the build-up of organic matter in peat is an important store of carbon, when peat decomposes due to bog degradation it releases carbon dioxide (CO_2) and methane (CH_4) into the atmosphere. In some places, bogs appear to be carbon sinks, but as temperatures increase or they are damaged, bogs may become sources of CO_2 being released into the atmosphere. Consequently, peatlands can switch from being ameliorators of, to contributors to global warming. Moreover, increased carbon emissions from peatlands will have a positive feedback on both temperature and rates of carbon emissions in the future (Grover and Baldock 2012). Determining the carbon budget of peatland ecosystems is now an important aspect of management and restoration projects due to the impact of carbon dioxide and methane sources and sinks on the climate (Bonnett et al. 2009).

The total carbon store of peatlands in the Snowy Mountains is estimated to be about 3,550 Megagrams (Mg), with net carbon storage rates over the past 60 years of 0.8–1.6 Mg per ha per year, which is similar to the rates of 0.2 to 2.3 Mg per ha per year found in other temperate peatlands (Hope and Nanson 2015).

Drivers of change in carbon storage

The value carbon source can be impacted by all 10 stressors and 6/17 threatening processes (Figure 8). Warmer temperatures are the main factor known to promote the decline and decomposition of peat

(Whinam and Chilcott 2002, Grover and Baldock 2012). In addition to temperature, Grover and Baldock (2012) found that the degree of saturation was one of the main factors affecting how readily peat decomposes. Dried peat experiences considerably more decomposition at the surface and the extent of decomposition increased more over smaller depths compared with wet bog peat. Grover and Baldock (2012) also found that different peat types (or substrate quality) are somehow protected from decomposition, perhaps due to the presence of decay-resistant polymers, antimicrobial agents or lipid surface coatings. Fluctuations in the water table height and storm flow events can also have an effect (Bonnett et al. 2009). Impacts like fire, stock grazing and hydrological changes caused by trampling of large mammals could also accelerate decay (Hope and Nanson 2015). Given that *Sphagnum* bogs have soil-carbon densities over twice that of non-*Sphagnum* peatlands (Loisel and Bunsen 2020), changes in the extent or growth rates of *Sphagnum* (i.e. due to fire, bleaching, trampling etc.) could also impact rates of carbon sequestration.

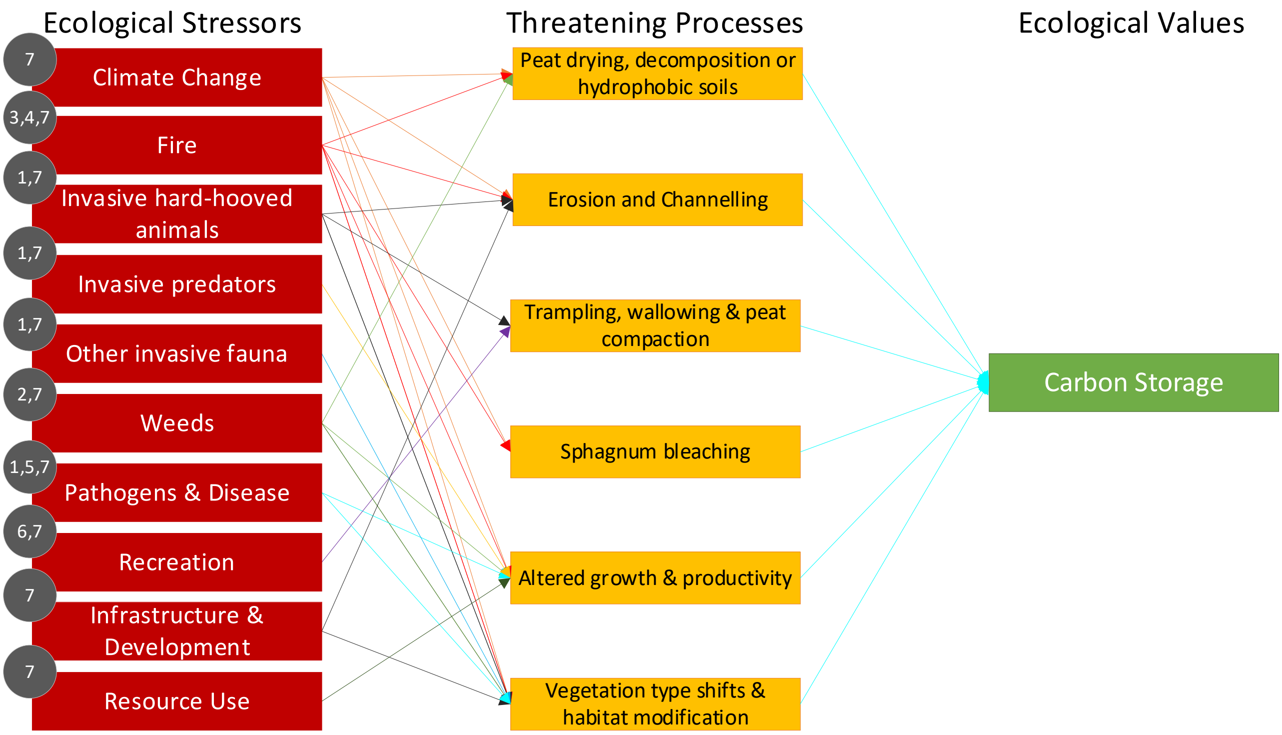

Figure 8 Subsection of the conceptual model for the bogs and fens focusing on the stressors and threatening processes that are causally linked to carbon storage specifically.

Potential management actions for carbon storage

There is consistent evidence that restoring peatlands can enhance the ecosystem service of carbon storage (Rowland et al. 2021). Because water content can dampen the effects of temperature on peat decomposition, rewetting areas of dried peat could decrease carbon emissions from peat in the Australian Alps. Grover and Baldock (2012) state that their results suggest that leaky weirs that increase water retention, and replanting wetland species may decrease decomposition. Also, actions to raise the water table, particularly where drainage lines have been entrenched by trampling will enhance the ability to store and further sequester carbon (Grover et al. 2012). These actions would be positive in terms of maintaining ecosystem productivity and limiting CO_2 emissions to the atmosphere. Additionally, research from the northern hemisphere on bogs that have been drained for peat mining, suggests that rehabilitation may return poor quality bogs acting as carbon sources back into sinks — or at least slow decomposition rates (Grover and Baldock 2012). In these cases, re-wetting the peat is suggested to be the critical requirement for their rehabilitation (Price et al. 2005, Grover and Baldock 2012). This may also be applicable to Australian situations where peatlands have been damaged by fire and experience subsequent drying. Hope and Nanson (2015) state that the general principles for enhancing carbon storage in peatlands consist of actively reducing disturbance and promoting water retention.

Despite the availability of some management options for peatlands that have been damaged, Grover and Baldock (2012) suggest that it is unlikely that the breakdown of largely natural, undeveloped areas of peat can be arrested, other than by halting net increases in temperature through general reductions in greenhouse emissions.

Potential indicators of carbon storage condition

There are many indicators and methods that can be used to measure the carbon budget — or parts of the full budget (e.g., carbon storage or the levels of decomposition of peat) — of peatlands (Lindsay 2010). The total carbon budget is the net sum of a variety of biological, physical and chemical processes that are also of inherent individual importance. Bonnett et al. (2009) and Worrall et al. (2003) summarise the carbon budget for peatlands into three inputs: (1) CO_2 sequestration from the atmosphere by primary production, (2) Input of Dissolved Organic Carbon (DOC) and inorganic carbon as part of rainwater, and (3) Input of inorganic carbon from weathering of underlying strata. The outputs include: (1) CO_2 and CH_4 to the atmosphere as part of plant soil organism decomposition, and (2) Fluvial outputs – DOC, Particulate Organic Carbon (POC), Dissolved Inorganic Carbon (DIC) and dissolved gas. Bonnett et al. (2009) suggests that the most important fluxes of carbon to measure in a restoration and management context are the gaseous fluxes (particularly CO_2), and the organic fluvial fluxes of DOC and POC.

Decomposition of peat is a fairly common indicator that can be measured either directly (loss of mass of the original material) or indirectly (CO_2 produced from decomposition by microbial activity). Samples can be extracted from the field and incubated in a laboratory to account for external factors that influence decomposition (such as temperature, water content, bulk density, substrate quality) or collected *in situ* to quantify the combined effects of these factors (Grover and Baldock 2010). Further field research to determine the carbon balance of the peatlands should be undertaken, specifically to validate estimates for peat growth (Hope and Nanson 2015).

Grover and Baldock (2010) recorded CO_2 emissions from dry and wet bog peats with chambers that contained a soda lime CO_2 trap, which has been found to be quantitative and reliable. Grover and Baldock (2012) directly measured peat chemistry to ascertain how decomposed the peat was. The study used solid-state ^{13}C NMR spectroscopy to define the carbon chemistry and the extent of decomposition in continuous profiles of bog peat and dried peat. Grover et al. (2005) measured the concentrations of total and plant-available elements and the chemical composition of the organic carbon to calculate a measure of the extent of decomposition. Hope and Nanson (2015) estimate the size of the organic store in peatlands in the ACT and the Snowy Mountains by combining mapping and depth data. They also use dated peat sections to derive recent and longer-term accumulation rates to get a first approximation of their significance as sinks or sources of carbon (over decadal and millennial timescales).

Sphagnum moss is a critical component to the accumulation of carbon into peat. Loisel and Bunsen (2020) found that in South America, *Sphagnum* deposits are associated with larger soil-carbon stocks, higher rates of peat-carbon accumulation, and greater peat masses than their non-*Sphagnum* counterparts, with *Sphagnum* bogs being characterized by soil-carbon densities over twice that of non-*Sphagnum* peatlands (including fens). Consequently, the health of *Sphagnum* moss might also be an indicator of potential carbon storage.

Ecological Stressors

Ecological stressors will frequently interact with each other to create negative feedbacks and amplify their impacts. For instance, drought and increased fire frequency can result in bogs being drier, more flammable and thus more susceptible to weed invasion that can reduce the overall condition of the ecosystem (Wild and Magierowski 2015). Here, the impact of stressors on threatening processes and values are generally considered in isolation of the impacts of other stressors, although this may become a larger focus in future versions.

Climate change

Climate change is listed as the largest threat to bogs and fens in Australia, even though the future implications and specific details are as yet unclear (Department of the Environment 2015). For instance, ACT Government (2017) suggests that climate change impacts are already occurring at the Ramsar site Ginini Flats Wetlands Complex, and predict moderate to high consequences with high risk for that site. McMahon et al. (2015) also ranks climate change as having the highest level of severity on the community, with a likely and wide-ranging impact.

As the climate changes, Australian bogs will likely experience altered rainfall, increased ambient and soil temperature, increased atmospheric carbon dioxide levels, and changes in snow cover depth, duration and melt (ACT Government 2017). Bogs and fens are particularly vulnerable to such changes in climate because their health and presence are influenced by specific physical conditions (e.g. low temperatures, permanent water, acidic pH and periods of snow cover) (Department of the Environment 2015). The community is considered to be at the limits of its possible range, and therefore options for adapting to new warmer and dryer conditions via shifting distributions is not possible (Department of the Environment 2009).

One of the key research challenges is to understand the resilience of bogs and fens to climate change generally, but also understand which factors (e.g. condition, presence of stressors) influence the resilience of bogs to climate change across Australia. ACT Government (2016) state that resilience should be measured as an outcome of successful adaptation by identifying and tracking measurable and repeatable indicators to evaluate resilience across communities.

Threatening processes of climate change and impacts on values

Climate change is likely to have multiple, interlinking negative consequences for bogs and fens. Climate change impacts all ecological values via 10/17 threatening processes (Figure 9). Although many reports and journal articles suggest likely impacts on bogs and fens, most suggestions are based on expert opinion because quantitative studies linking climate to ecological impacts are, to our knowledge, not currently available. It is possible that the combined effects of climate change, particularly increased temperatures and altered rainfall patterns could result in *Sphagnum* peatlands not being able to persist into the future, especially those at the hottest and driest margins of their distribution (Whinam and Chilcott 2002). Climate change will also likely have direct impacts on other stressors such as increased frequency and intensity of wildfire (Hope et al. 2009), and invasive species if sites can act as potential refugia or novel appropriate climate niche for new species (Rowland et al. 2023).

Hydrology and the water table

The hydrological functioning of bogs and fens will likely be impacted by the predicted changes in climate in several ways. Changes in rainfall and snowmelt patterns will likely lead to changes in hydrology, including lower water table levels and decreased stream flow. Such processes may lead to a series of feedback mechanisms altering the state of peat retention, the hydrological cycling of the system, and place pressure on the bogs' long-term persistence. Specifically, lower water tables can influence available water and primary productivity, this can then result in declining peat creation and storage and invasion by less water-tolerant species such as grasses and shrubs (ACT Government 2017). Increases in soil temperature may increase evapotranspiration, decreasing available soil moisture (ACT Government 2017). Ultimately, such impacts may result in increased erosion of disturbed peat surfaces or even reduced peatland area (ACT Government 2017).

Although snowpack is important for the slow release of water into the bogs as they thaw, snowcover itself is not a required factor for their hydrological health as they are maintained by summer groundwater rather than winter climatic regimes (Department of the Environment 2015). However, changes in snow cover depth, duration and melt patterns could impact water availability when in drought (ACT Government 2017).

The hydrological impacts on bogs and fens from changes in climate can potentially be severe. *Sphagnum* peatlands only occur in areas where the water table is high and stable, such that there is a constant supply of surface or seepage water (Whinam and Chilcott 2002). Additionally, the historical distribution of *Sphagnum* bogs is largely limited by evapotranspiration in the warmest months (Whinam and Chilcott 2002). If both of these limiting factors are predicted to change in the future then large declines in condition might be expected. Yet as pressures on water availability increase, so too does the importance of the communities functional role in regulating water release and flow downstream (Department of the Environment 2009).

Flora and Fauna

Climate change is predicted to have a range of impacts on the flora and fauna of bogs and fens. Increased temperatures and UV radiation over summer can commonly result in decreased growth and bleaching of *Sphagnum*, which has become more pronounced over the last few decades. Conversely, increased atmospheric carbon dioxide may result in increased primary productivity of vegetation, including *Sphagnum* (ACT Government 2017). It is currently thought that declines in the extent of *Sphagnum*-dominated communities in the ACT and NSW over several decades is linked to declines in water availability (Whinam and Chilcott 2002, Hope et al. 2009). Hope and Nanson (2015) predict that *Sphagnum* moss will spend longer periods with negative growth, and so may become restricted to well-shaded areas.

Reduced snow depth and persistence increases both the impacts of cold and frost conditions, and exposure to intense winds and solar radiation to flora and fauna (Department of the Environment 2015). Reduced snow cover can lower the potential for recovery from past disturbances, may change growth characteristics of the bog acrotelm, and results in less-compacted *Sphagnum*, (ACT Government 2017).

Climate change can ultimately influence community composition and extent. For instance, changes in temperature may reduce the frost hollow effect, permitting increased growth and dominance of woody species (ACT Government 2017). Hope et al. (2009) states that, because the ACT has relatively lower rainfall compared to subalpine areas of NSW and Victoria it is likely to experience more contraction of bog extent, shifting from *Sphagnum* bog communities to *Empodisma* fen or sod tussock communities.

Peat formation and stability

The formation and stability of peat is at high risk of being impacted by changes in climatic conditions. For instance, hot and dry conditions lead to decreased production rates of peat (Hope 2003, Growcock and Wright 2007). Additionally, increased temperatures will increase oxidation and decomposition of already established peats (ACT Government 2017). Consequently, rates of carbon sequestration are sensitive to changes in the climate. As temperature increases, the balance between carbon accumulation and release may be switched towards release (Grover et al. 2012). It is likely that dry and warm phases, particularly hot summers, cause peatlands to become carbon sources (Hope and Nanson 2015). If this occurs, peat bogs have the potential to be contributors to climate change, as increased carbon dioxide emissions from decomposing peat will have a positive feedback on both temperature and future rates of emissions (Grover et al. 2012).

The predicted increased frequency and intensity of precipitation events may increase erosion of disturbed peat surfaces, which in turn could alter the state of peat retention and potentially result in reduced peatland area (ACT Government 2017). Soil desiccation is likely to occur around the margins of bogs and fens in particular, which could result in *Sphagnum* bog converting to tussock grassland (Hope and Nanson 2015). Additionally, reduced snow cover can result in increased erosion from exposure to intense winds and rain (Department of the Environment 2015).

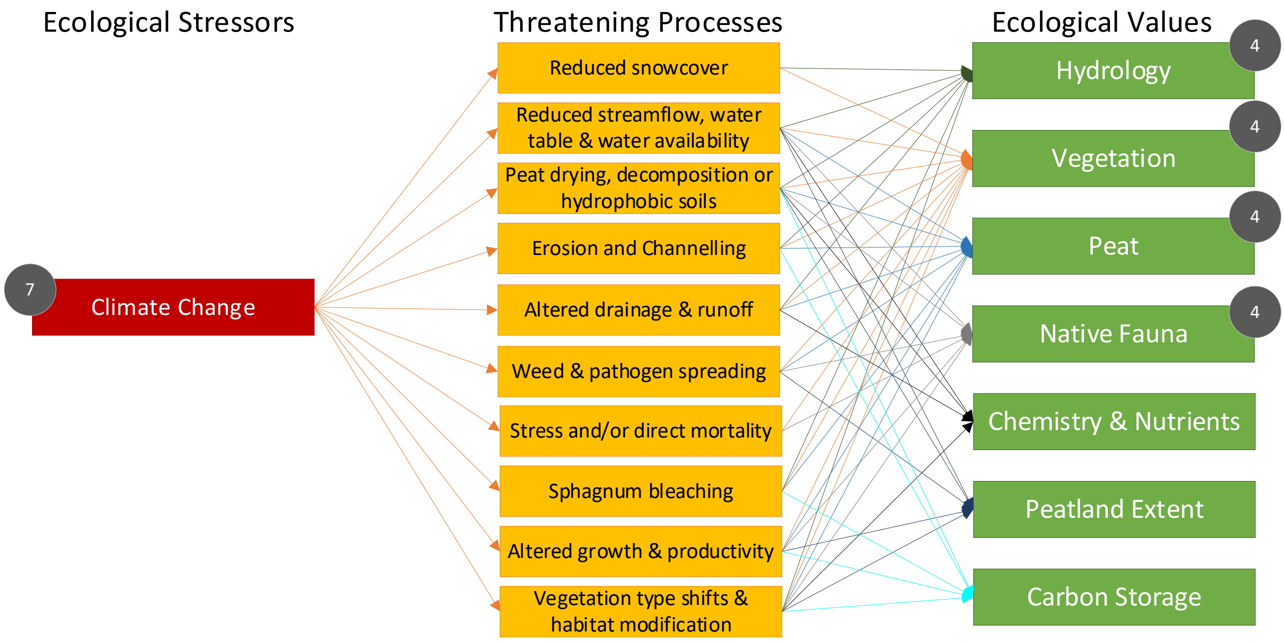

Figure 9 Subsection of the conceptual model for the bogs and fens focusing on the threatening processes and ecological values that are impacted by climate change specifically.

Potential management actions for climate change

Given that biodiversity is projected to experience high pressures under climate change across Australia, Prober et al. (2015) suggest that ecological management needs to move away from principles aiming to restore ecosystems towards pre-European states. Instead, a transition into managing what *might be attainable and reasonable* is needed, by defining new principles that acknowledge change and aim to guide it. Consequently, new principles, goals and actions are required that acknowledge and facilitate change processes that might be substantially different to traditional approaches (Prober et al. 2015).

Making management decisions that aim to help bogs and fens adapt or mitigate the effects of climate change is difficult without the appropriate underlying knowledge on which processes and functions are sensitive to, for instance, changes in temperature and water availability (Rowland et al. 2023). One of the 25 research priorities listed in Rowland et al. (2023) states that:

> Research is needed to identify interventions that could increase peatland resilience to climate change and under what circumstances (if any) should management occur under a changing climate?

Some key management techniques used in these systems for other threats (e.g. fire recovery) may be suitable for mitigating some of the impacts of climate change. For instance, leaky weirs aim to hold and spread moisture through the peat and reduce erosion. Consequently, they could be beneficial for retaining more run-off in times of drought or reducing erosion in heavy rainfall events or if snow cover is lacking. Similarly, shade cloths could potentially decrease the effects of solar radiation, heat and reduced humidity by reducing evapotranspiration and creating a humid micro-climate shaded from direct sunlight (noting this is not a feasible long-term or widespread solution).

Research needs to be conducted on the potential uses of different management techniques to reduce the effects of climate change on bogs and fens so as to understand what might be realistic targets to set. Rowland et al. (2023) highlights that more needs to be understood before timeframes for the realistic persistence of peatlands can be provided, which will be essential for enabling managers to alter current conservation objectives if they are impossible or impractical to maintain with climate change. Consequently, before new management goals can be set, the actual impacts of climate change and their likely consequences on the ecological community in the future need to be understood.

Potential indicators for climate change

Physical changes in climate

The choice of which weather variables to consider, over which period of the year and which metric to use should in this situation be approached systematically as there is limited *a priori* knowledge and could include potentially large numbers of plausible competing weather signal hypotheses (van de Pol et al. 2016). Physical indicators could include variables such as mean, maximum or minimum temperatures, heat waves (for example, number of days above 30°C), precipitation, snow cover, evapotranspiration or humidity.

Impacts of physical changes in climate on bogs

Many bog and fen ecological values are predicted to be impacted by changes in climate. Potential indicators of impacts on these communities include: water table height, water availability, downstream flow (regulated water release), soil wetness/desiccation, peat creation rates, rates of oxidation and decomposition of established peat, peatland area, erosion, *Sphagnum* bleaching, changed vegetation productivity and growth and species composition (e.g. invasion of less water-tolerant species or shifting *Sphagnum* bog communities to *Empodisma* fen or sod tussock communities). Additionally, changes in the rates or impacts of other stressors such as fire, invasive species, pathogens and disease are also likely to be escalated with climate change.

Fire

Peatlands are highly sensitive to fire. While fire is known to have occurred in peatlands over the Holocene and they have evolved with it, fire is not a process that supports the ecosystem function of these communities (e.g. the vegetation does not require fire for germination processes) (Department of the Environment 2015, McDougall et al. 2023). Fire includes both bushfire, planned burning, and back-burning used during fire suppression (McMahon et al. 2015). Fire is rated at the highest threat severity category for both McMahon et al. (2015) and Department of the Environment (2015). It might take *Sphagnum*-dominated bogs between 15 and 45 years to recover from fire without peat burning (Walsh and McDougall 2004), but up to 90 years to recover if peat fires have occurred (Cheal 2010, Wild and Magierowski 2015). Repeated burning at short intervals, particularly under drought conditions, will have detrimental impacts on the community (Whinam et al. 2010, Department of the Environment 2015). Fens tend to restabilise within a few weeks after fire and in the absence of erosion and incision, as the grass-like sedge *Carex gaudichaudiana* readily resprouts after burning which forms an effective filter and spreads water out across valley floors (Hope et al. 2012).

Ground fires, or peat fires, can also occur in bogs and fens when organic soils are consumed through smouldering combustion. These fires can last for months after a bushfire front has passed and are extremely damaging to the ecological community (Prior et al. 2020).

Landscape-scale fires in the high-elevation areas where bogs occur were generally considered rare because of the low incidence of extreme fire weather conditions, but are now becoming increasingly common as weather becomes hotter and drier (McDougall et al. 2023). As the climate continues to get warmer and drier with climate change, the potential for increased frequency of high intensity fires developing each year is significant and is already resulting in landscape-wide vegetation and soil change in alpine areas. Bogs and fens across the ACT for instance have experienced numerous wildfires over the last few decades. Over the last 37 years, 35 sites have burnt three times, 35 sites have burnt twice, 13 sites have burnt once and only one site has not burned (McLean et al. 2023b). Given that post-fire recovery can take between 15 and 45 years, peatlands are already burning too frequently.

Threatening processes of fire and impacts on values

Fire impacts all ecological values via 12/17 threatening processes (Figure 10). Fire damage significantly increases the susceptibility of peatlands to other threats, including introduced fauna and flora and climate change. The re-establishment of vegetation and habitat can take many years, leaving these communities at higher risk of other stressors such as weed invasion and increased numbers of large animals as they are able to gain access to a larger proportion of a bog (Department of the Environment 2009).

Flora and fauna

Much of the vegetation that occurs in bogs and fens is sensitive to fire, particularly *Sphagnum* moss. Fire can impact bogs through permanent changes to the structure and species composition of the community, for instance more fire-tolerant rhizomatous sedges may become dominant over *Sphagnum* (Department of the Environment 2009, McMahon et al. 2015, ACT Government 2017). Such shifts in community composition could persist for decades (McMahon et al. 2015). Ground fires are particularly damaging and often kill plant stems, roots and propagules because the peat burns for long periods, and they can remove the physical soil substrate in which plants grow (Prior et al. 2020).

Ultimately, bogs impacted by fire could transition into upland grassland or heathland ecosystems, as has already been seen in small bogs impacted by fire in Victoria (McMahon et al. 2015, Wild and Magierowski 2015).

Immediately after fire there can be complete loss of vegetation, although *Sphagnum* mounds do not appear to completely disintegrate but rather remain in the system bleached and burnt. *Sphagnum* moss depends on the survival of remnant unburnt fragments for regeneration, whilst shrubs such as *Epacris gunnii* and *Richea continentis* rely on seedling recruitment to re-establish post-fire. Both of these processes take a long time, leaving the bog environment extremely vulnerable to prolonged soil erosion and weed invasion in the interim (Department of the Environment 2009).

If *Sphagnum* is completely lost from a site, the moss and the bogs that depend on it for permanently moist conditions may become locally extinct without importation of live plants (either by fragmentation and movement by water down the catchment, or by human intervention) (Walsh and McDougall 2004). Whinam et al. (2010) found that when more than 10% *Sphagnum* cover survived (within quadrats 75 x 2 m^2), cover increased relatively rapidly to 80% by 3 years. However, quadrats with less than 10% cover surviving showed little or no increase. This shows that regeneration occurs by the expansion of the larger patches (with >10% cover) of *Sphagnum* (Whinam et al. 2010). This same 10% threshold was found in damaged blanket bogs in England (Clarkson et al. 2017). Additionally, Clarkson et al. (2017) found that *Sphagnum* did not regenerate if it had been severely burnt, was exposed on the tops of dead hummocks, or in dry areas where the water table had dropped significantly.

Fire results in an immediate loss of habitat for native animals (Department of the Environment 2009), and the resulting long-term habitat degradation can also lead to declines in native fauna, such as the Alpine Water Skink (McMahon et al. 2015).

Hydrology

Fire can have a large impact on peatland hydrology. The removal of functionally important species after fire (such as *Sphagnum* moss) can have subsequent impacts on water holding capacity, water quality and erosion rates. Channelisation and stream incision can occur and alter the hydrology, and increased dried peat area can also impact hydrology and reduce peatland area (ACT Government 2017). Dried peat experiences greater water table fluctuations, making it more prone to decomposition, potentially rendering it irreversibly unsuitable as a substrate for *Sphagnum*, and increasing its susceptibility to both erosion and future fire damage (McMahon et al. 2015). Fire also results in increased sedimentation from surface runoff of bare areas (ACT Government 2017).

Peat

The removal of vegetation by fire can lead to erosion and incision (Department of the Environment 2009), increased sedimentation from surface runoff of bare areas (ACT Government 2017). Fire damage can cause both decomposition of peat and entrenchment of drainage lines, leading to the drying and shrinking of peatland extent. After fire, exposed, bare peats are at risk of erosion from livestock and introduced ungulates, and are more susceptible to weed invasion (McMahon et al. 2015).

Ground fires have long-term effects on bog functioning and can compromise whole geomorphological features and can lead to state changes (Prior et al. 2020). After peat fires, hydrophobic ash has been found to remain on the surface, and the peat had a neutral pH unlike the normally acidic bogs. These areas were also susceptible to frost heave and erosion after being burnt (Wild et al. 2010). Burnt peats can become hydrophobic when vegetation cover is completely removed and the exposed burnt peats developed a hard crust preventing water infiltration (Clarkson et al. 2017).

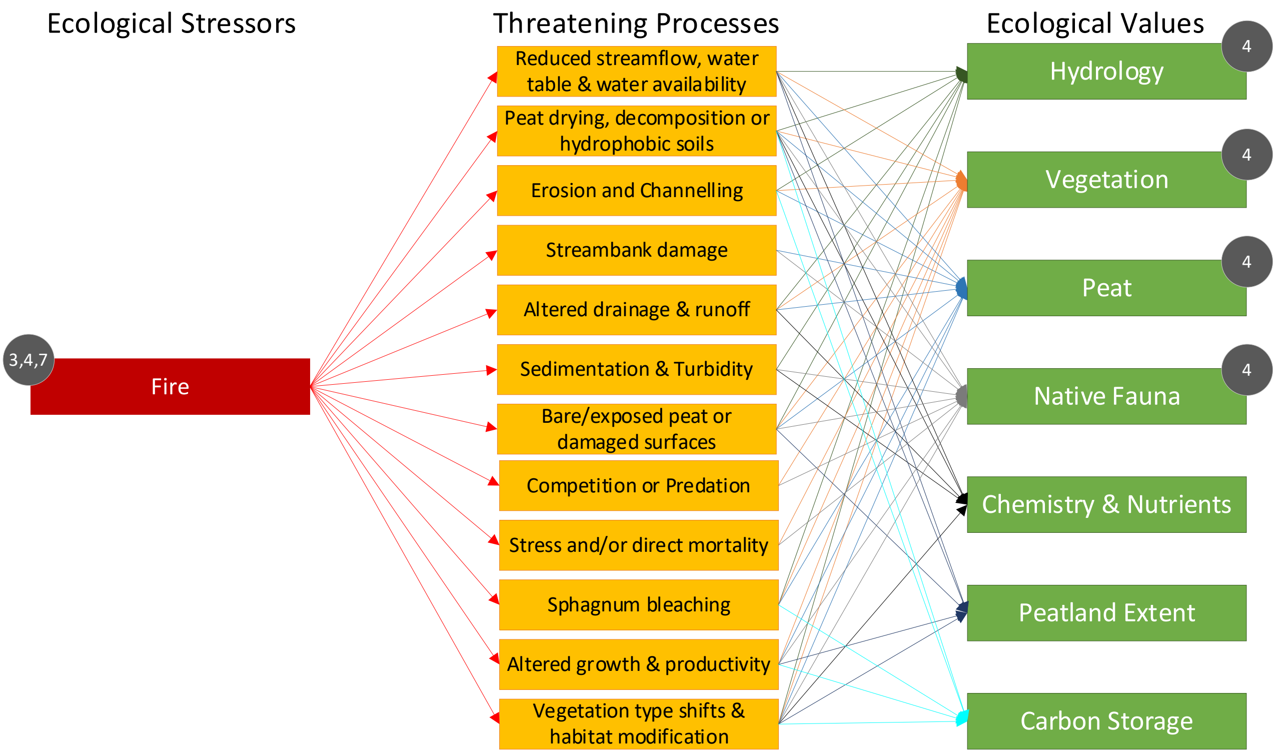

Figure 10 Subsection of the conceptual model for the bogs and fens focusing on the threatening processes and ecological values that are impacted by fire specifically.

Potential management actions for fire and thresholds

It is important to plan for and manage the effects of fire on peatlands, with a focus on minimising both the threat and impacts of fire on the ecological community (Department of the Environment 2015). The approved conservation advice for the national Alpine *Sphagnum* Bog and Associated Fens Community states that it is critically important to develop and implement suitable fire management strategies to prevent further loss of functionally important species and community integrity from the ecological community (DEWHA 2008).

The National Recovery Plan (Department of the Environment 2015) suggests several high priority management actions for managing fire, including:

a) Maintain accurate fire history via mapping of extent, frequency, severity (or intensity) and regeneration
b) Incorporate appropriate management guidelines for fire suppression in the ecological community as part of fire management plans
c) Improve knowledge about the importance and locations of the ecological community for field staff and fire management operators
d) Avoid negative impacts to the ecological community from fuel reduction burns
e) Avoid damage to the ecological community from activities associated with fire management operations (e.g. control line construction vehicle access, back burning)
f) Develop an ecological procedure for assessing fire impacts and required responses (e.g. additional protection) to mitigate fire impacts and monitor regeneration over time
g) Develop and implement targeted management responses for fire affected areas (for example through restricting access in the post fire recovery period).

Prevention and slowing of fire

<u>Firefighting chemicals</u>

Fire is known to have devastating effects in peatlands, yet the use of firefighting chemicals must be considered carefully. Retardants and suppressants have harmful impacts on aquatic ecosystems (Styger 2019). The impacts of retardants and suppressants on waterways have been shown to dissipate once sufficiently diluted, but peatlands often have low flushing capacity, meaning dilution of these chemical will be slow and impacts will not dissipate quickly. As a result, the use of firefighting chemicals is a concern and considerable effort should be made to not apply chemicals directly to bogs and fens. The United States Department of Agriculture has enacted a 300-foot buffer around all waterways for the application of fire retardants and suppressants, but this is not always practical if waterways are too common and extensive. Of note, toxicity from firefighting chemicals is much lower on soils with high organic content than coarse-textured soils which tend to leach chemicals into streams and waterbodies (Styger 2019). Following recommendations from (Styger 2019), guidelines should be developed specifically for peatlands and high altitude wetlands and waterways.

<u>Preventing peat fires</u>

Moisture content is the primary control on whether organic soil will combust. Consequently, having an understanding of the volumetric moisture content in peat soils can give an indication as to whether peat fires might occur if they were to experience a wildfire. Prior et al. (2020) found that a hand-held meter that measured volumetric moisture content using time domain reflectometry could be used to satisfactorily predict organic soil combustion. If it is known that peat soils are likely to burn, actions could potentially be taken to rewet the peat to prevent devastating and long-lasting peat fires. Maintaining an appropriate moisture regime may be critical to avoid long-term loss of peatlands from the impacts of fire (Whinam et al. 2010, McMahon et al. 2015). To do this, sprinkler systems to wet the surface and ground spikes to add water beneath the surface layer have both been trialled in Tasmania, with the outcomes not yet available (Kathryn Storey & Jenny Styger, pers. comm., 2021).

Once a peat fire is occurring, thermal imaging drones can potentially be used to identify current peat fires. At peat fire locations, the burning edges of the soil fire can be dug out and wetted (if possible). Although digging trenches through the peat is certainly damaging in itself, it is likely less damaging than having the peat burn extensively throughout a whole site, potentially for months (Kathryn Storey & Jenny Styger, pers. comm., 2021).

Recovery after fire

Hope et al. (2009) stated that from observations after the 2003 fires in New South Wales (NSW) and the ACT, the prevention of erosion and the re-wetting of areas of peatlands that appear to be drying out were the most critical concerns. Any post-fire rehabilitation program must slow surface flows to prevent flowline entrenchment and to create pools of surface water where *Sphagnum spp* can regenerate and the pooled water can spread laterally through the peats, thereby restoring the hydrologic regime of the bogs and fens (Good 2009, Hope et al. 2009, Macdonald and McLean 2023). To our knowledge, no restoration work has been focused on fens as they are believed to recover more readily. However, if needed, many of the techniques described below could be used in fens.

Several management techniques exist to restore peatlands after fire, including leaky weirs, solid weirs, shading, fertiliser, transplants of key vegetation species. The effectiveness of these techniques has been studied to different degrees.

<u>Weirs</u>

One of the main methods used for restoring burnt peatlands are the use of weirs or dams. Impermeable marine plywood weirs were trialled after the 1983 fire in the ACT but were found not to effectively block channels that had permanent flow (Hope et al. 2009). Since then, permeable, or leaky weirs (coir logs or straw bales) have been used in the ACT. The key objectives of leaky weirs are to (1) prevent, halt and reduce erosion/incision of peat by slowing surface channel flows and trapping sediment, (2) increase the wetness of the peat by slowing and spreading water to create moist surface areas and re-wet desiccated peat and raising the water table, and (3) increase vegetation cover and recovery speeds by creating moist surface areas in which *Sphagnum* and other peatland species could recover (Hope et al. 2009, Clarkson et al. 2017).

Despite leaky weirs being one of the main post-fire restoration actions utilised, no previous studies have investigated the effectiveness of leaky weirs in achieving their aims. As described in Macdonald and McLean (2023), there is currently a research project run by both Parks and Conservation, and the Office of Nature Conservation in the ACT Government that will be the first to quantitatively assess how useful leaky weirs are at preventing and reducing peat erosion, increasing peat wetness and promoting the recovery of vegetation, but also, whether improvements could be made to increase their effectiveness.

<u>Shading</u>

Sphagnum moss favours shaded areas, with 70% natural shading by other plants found to be ideal (Whinam and Buxton 1997). Dry conditions can lead to *Sphagnum* hummocks bleaching, and high levels of UV are also thought to contribute (Good et al. 2010, Hope et al. 2016). The degree of evapotranspiration during summer is also important, as *Sphagnum* mires in the Australian Alps have been found to be climatically limited by evapotranspiration in the hottest month (Whinam et al. 2003b). The removal of shrubs and graminoid cover by wildfire therefore reduces the ability of *Sphagnum* to recover rapidly.

Shade cloths over *Sphagnum* after the 2020 Orroral Valley Fire in the ACT found shade cloths significantly improved the recovery of live *Sphagnum* and reduced ongoing mortality after the fire (McLean et al. 2023c). Artificial shading was also used after the 2003 wildfires to enhance recovery in bogs across Kosciuszko National Park and Namadgi National park (Hope et al. 2016). Whinam et al. (2010) suggested that horizontal shade cloths not only provided shade protection, but also reduced evapotranspiration, wind desiccation and protects moss from high UV levels. Artificial shading can also protect plants from strong sunlight and high summer temperatures, retain humidity, and protect from ice and frost damage and may limit grazing (Hope et al. 2016).

For details on the research on shading previously undertaken, see Hope et al. (2016), Good et al. (2010) and Whinam et al. (2010). Their research found that all native plant species (total percentage vegetation cover for all native species) recovered significantly faster with shading than without, with forbs being the only lifeform that showed significant increases in cover over time compared to unshaded controls. Unfortunately, there was insufficient data to quantitatively analyse the benefits of the restoration techniques on the recovery of *Sphagnum* moss (predominantly *S. cristatum*), although there was some indication that shading promoted early establishment and growth of surviving *Sphagnum* plants (Whinam et al. 2010).

Transplantation/fertilisation

Restoration of fire-damaged bogs and fens often involves the enhancement or re-establishment of a stable *Sphagnum* moss and *Empodisma spp*. vegetation cover. *Sphagnum* transplants have been found to act as nuclei for future growth and spread, particularly under favourable shade and humidity conditions (Clarkson et al. 2017). The addition of fertilisers to speed vegetation recovery and promote the survival of transplanted species is also an option for management after fire. There is some suggestion that fertilisers can help to kick-start vegetation recovery, although the effects differ for different species (Whinam et al. 2010, Clarkson et al. 2017). However, the use of fertiliser for the outcomes given the costs and effort may not be worth focusing on (Geoff Hope, pers. comm., 2020). Additionally, the addition of fertiliser causes short-term elevation in nutrients (estimated at 2 years) which could increase the potential for invasion by higher-nutrient requiring weeds (Clarkson et al. 2017).

Potential indicators for fire

Past fire history

Indicators of past fire history can include fire extent and frequency. Fire extent can include the extent of fire impacts, from part or all of a single peatland to entire peatland clusters or regions (McMahon et al. 2015). Fire frequency is important to record because peatlands may not fully recover between successive fires if recurrence intervals are insufficient (perhaps less than 40 to 90 years) (McMahon et al. 2015).

Impacts of fire

There are many potential measures of the impacts of fire on bogs and fens which differ depending on how soon after the fire sites are assessed. Good (2009) suggested measuring the amount of vegetation lost during the fires, if peat incision had begun and if the soils had become hydrophobic following the fires. Whinam et al. (2010) measured fire damage in terms of the degree of preservation of the biomass and peat profile. Five categories of damage were identified, including (i) unburnt, (ii) burnt but moss cushion intact,

(iii) burnt cushion margins, (iv) charred but root mat intact and (v) burnt and incised. Identifying areas where stream incision has begun, or that are highly susceptible to stream incision is also important (Carey 2004, Robertson et al. 2019)(Geoff Hope, pers. comm., 2020). Evidence of stream incision or increased susceptibility can include:

- Drainage line walls nearly vertical and around 30 cm high
- Signs of active erosion which include side-wall caving, shearing, soil loss from the bank into the stream bed, or clear evidence of soil loss, cracking and peat masses falling into the channel
- Undercutting of walls on the outside of bends, slumping of bank into stream
- Water falling steeply down small steps (e.g. 10-40cm)
- Evidence of drained pools
- Evidence of abandoned minor channels in favour of a central drainage line
- Evidence of peat fire along channel margins
- Evidence of earlier incision and drying.

Invasive hard-hooved animals

Invasive hard-hooved animals are significant threats to bogs and fens, and include feral horses, deer, pigs and cattle. McMahon et al. (2015) ranked feral horses and domestic stock as having the highest severity impacts, followed by deer and then pigs. While the National Recovery Plan for bogs (Department of the Environment 2015) also ranks horses and stock highest, but deer and pigs as both equally high severity. Domestic stock are included in the 'Invasive hard-hooved animals' indicator because the impacts of feral and domestic animals are similar. Feral pigs are nationally listed as a key threatening process under the EPBC Act due to predation, habitat degradation, competition and disease transmission. Feral horses and deer are also listed as key threatening processes.

Compared to other ecosystems like forests or grasslands, our understanding of the impacts of large herbivores on peatlands is limited (Pellerin et al. 2006, Robertson et al. 2019). Rowland et al. (2023) states that one of the 25 priority research questions for bogs and fens is to understand the relationship between ungulate density and impacts on peatlands.

Threatening processes and impacts on values

Hard-hooved animals adversely impact all ecological values of bogs and fens via 12/17 threatening processes, including trampling, grazing, peat compaction, wallowing, pugging, trenching and redirection of flow (Figure 11) (Department of the Environment 2015). Pigs also cause negative effects from rooting for underground plant parts and invertebrates (especially in moist soils), predation, competition and disturbance of native animals, and spreading of the root-rot fungus *Phytophthora cinnamomic* (Hone 2012, Bengsen et al. 2017).

Hydrology

The hydrological functioning of bogs and fens can be impacted by many processes caused by hard-hooved animals. For instance, pig and deer wallowing in pools can change the hydrological regime of the area (ACT Government 2017). Wallows change bog sites into "muddy quagmires" which can lower water quality by increasing suspended sediment and alter the chemistry (e.g. nitrogen and phosphorous concentrations) (Pellerin et al. 2006). Additionally, direct deposition of urine and faeces can decrease water quality and alter nutrients within bogs. Trampling (especially by stock and horses) can prevent the water table from being maintained near the surface and trackways can alter the hydrology and water quality and potentially drain areas of peatland. Similarly, trampling and wallows can increase water turbidity and channels can change drainage and redirect flows, impacting the hydrology of these systems (Rowland et al. 2023).

Peat

All hard-hooved animals, but horses in particular, cause damage to streambanks and pond edges, disturbing waterway banks and channel beds, alter stream structure and function, cause stream bank slumping, increased peat erosion, and higher levels of sediment on the stream bed (Pellerin et al. 2006, Hope et al. 2009, Robertson et al. 2019). When horses sink into saturated soils they cause damage to streambanks that results in large clods of soil being dislodged and finer particles being transported downstream (Robertson et al. 2019). Pig rooting can create bare areas and expose peat which leads to drying (Hope et al. 2009, ACT Government 2017). Trampling also increases the surface cover of bare peat which can increase sensitivity to erosion and increase drying (Pellerin et al. 2006, Rowland et al. 2023).

Flora and fauna

Trampling, browsing and grazing by hard-hooved animals can impact the vegetation community via vegetation removal from browsing, selective grazing or trampling, facilitate exotic weed invasion, and can drive shifts to other vegetation types (Pellerin et al. 2006, Department of the Environment 2009, Rowland et al. 2023). Plants growing on waterlogged peaty soil are easily damaged by trampling, even at low levels (Pellerin et al. 2006). *Sphagnum* moss is particularly vulnerable to trampling and wallowing by hard-hooved animals as the moss is easily compacted, crushed and broken up. This can cause channels to form in the moss and can result in erosion and changes to natural drainage patterns which can increase bog drying (Department of the Environment 2009). In European countries, domestic stock are known to impact plant communities through browsing, grazing and trampling (Pellerin et al. 2006). Such impacts lead to decreased shrub cover and increased grass and sedge cover, decreased shrub growth and lower total vegetation biomass. Although Hope et al. (2009) suggested that stock can lead to increased shrubbiness or tussocks as they feed on the soft herbs between hummocks.

Invasive hard-hooved animals can have both direct and indirect effects on other animal species. Direct effects can include incidental consumption, trampling and interference, which can have substantial impacts on populations of some species such as ground-nesting birds. Indirect effects can include modifying habitats and food resources via changes in the structure, biomass and composition of vegetation, altered fire regimes, impacts on the physical environment (e.g. soil disturbance, compaction or erosion), re-distributing nutrients, competing for food, and increasing populations of shared parasites or predators (Foster and Scheele 2019). Changes to streambeds and banks and increased sedimentation can degrade aquatic habitat and impact aquatic fauna (Robertson et al. 2019). Pigs can potentially disturb Northern Corroboree Frog breeding pools, egg nests and non-breeding habitat (ACT Government 2017). Foster and Scheele (2019) found that horse grazing and trampling reduce breeding-habitat quality for Northern Corroboree Frogs, which could result in reduced reproduction success. Schulz et al. (2019) found both the presence and abundance of the Broad-toothed Rat declined as feral horse impacts caused the loss of vegetation cover from trampling and grazing. The Broad-toothed Rat cannot then disperse to more suitable habitat and is more vulnerable to predators. Altered vegetation structure and composition from these invasive species will also influence animal habitat suitability (Rowland et al. 2023).

Disease

These species can introduce and spread pathogens (Rowland et al. 2023). Pigs, in particular, are regarded as one of the most significant disease hosts with a large potential to act as vectors for outbreaks as they carry a number of livestock diseases such as bovine tuberculosis and foot and mouth disease (Mcilroy et al. 1989, Hone 2012). They are also known to spread the rootrot fungus (*Phytophthora cinnamomi*), which can cause changes in species composition and plant community structure (Hone 2012, Bengsen et al. 2017).

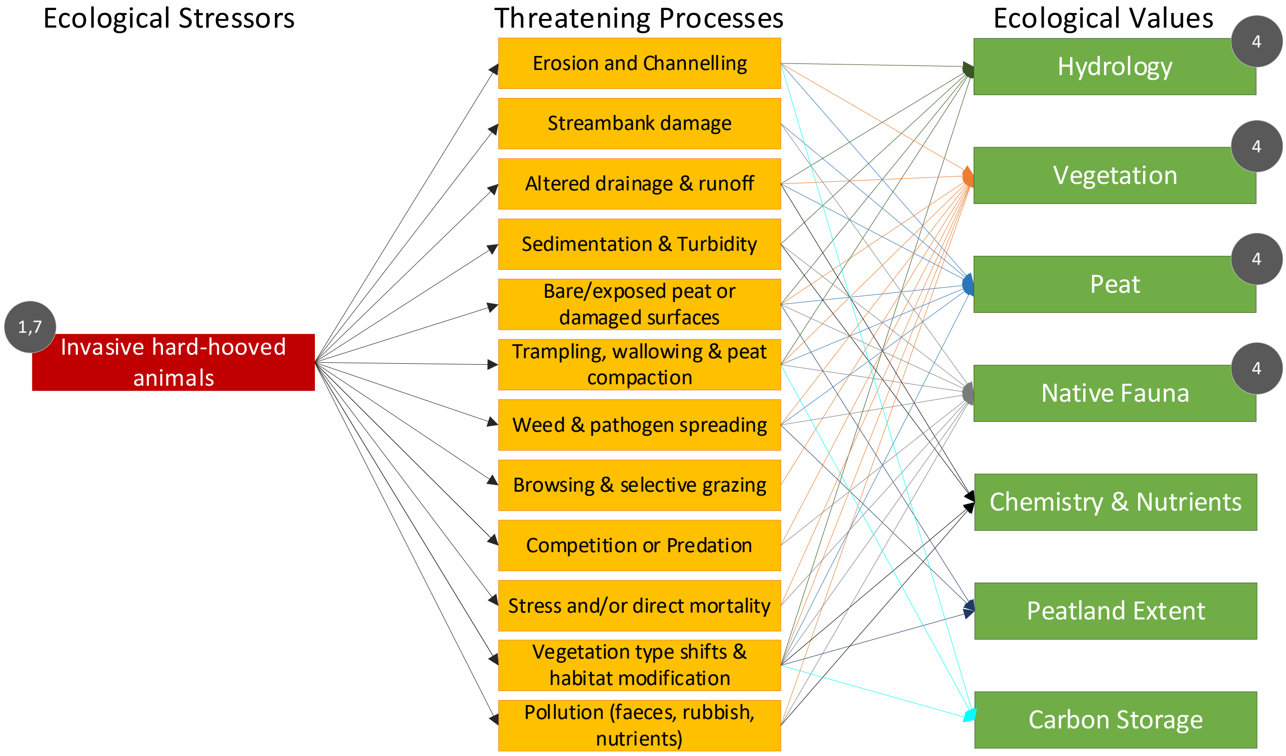

Figure 11 Subsection of the conceptual model for the bogs and fens focusing on the threatening processes and ecological values that are impacted by invasive hard-hooved animals specifically.

Potential management actions for invasive hard-hooved animals

Department of the Environment (2015) suggests that the aim for managing invasive hard-hooved animals is to minimise the impact on the ecological community. Management actions for invasive hard-hooved animals are well established throughout Australia. In addition to efforts to directly decrease numbers via shooting, baiting and trapping, a number of other management actions for reducing the impacts of these invasive species can be utilised. For instance, management to prevent impacts can include fencing or barriers to prevent individuals from accessing these areas (DEWHA 2008, Department of the Environment 2009, NSW Department of Primary Industries 2018). Pellerin et al. (2006) suggests that, after a thorough investigation of impacts in and around bog sites, wallows connected to waterways could be eliminated by drainage and filling with rock or cultivation if drastic measures are needed to be taken.

Potential indicators for invasive hard-hooved animals

Evidence of the presence/abundance of invasive hard-hooved animals

Evidence of the presence of these invasive species can include presence of scats, tracks/trampling, wallows, rub trees, pugging (Pellerin et al. 2006, Rodda 2019). Such measures of presence can give indications of the density of species (Pellerin et al. 2006). Density or abundance of invasive hard-hooved animals is harder to measure but can be estimated from camera arrays and aerial searches. With fewer individuals the level of signs of presence would be much lower (Pellerin et al. 2006). Pellerin et al. (2006) found that across the Bogong High Plains in Victoria it is apparent that sambar deer are widespread in the local bog communities as 80% of bogs showed readily observed signs of presence, while there were very low level incidence of deer sign at bog sites on the southern plateau of Mount Buffalo National Park. This disparity in frequency of deer sign between the two areas is likely attributable to a marked difference in the density of local deer populations.

Evidence of impacts of invasive hard-hooved animals

The impacts of hard-hooved animals on bogs and fens can be measured in several ways. For instance, Robertson et al. (2019) collected data on the degree of soil disturbance from pugging damage, stream bank stability classification, longitudinal profile characteristics of a drainage line, sediment level on the stream bed, number of defined animal tracks or pads, degree of grazing disturbance, foliage cover and percentage of native foliage cover. High resolution drone imagery could be used to map the extent of deer and pig wallows and ripping. Other potential indicators of impacts on these communities include: changes in vegetation community structure and composition, degree of damage to vegetation (especially *Sphagnum* moss), population sizes of key fauna, amount of bare ground, changes to hydrological features (such as water table height and drainage rates) as well as water quality (such as turbidity, nutrient levels), presence of new pathogens, and presence and densities of weeds (either woody or invasive).

Invasive Predators

Invasive predators are feral carnivores that have been introduced to Australia since European colonisation, including cats, foxes and wild dogs. ‘Predation by European red fox’ and ‘Predation by feral cats’ are listed as threatening processes under the EPBC Act. Both McMahon et al. (2015) and Department of the Environment (2015) estimate the severity of impacts to be moderate.

Threatening processes of invasive predators and impacts on values

Invasive predators predominantly impact native fauna populations via competition or predation, stress or mortality, altered growth and productivity (e.g. reproductive success) and pollution (faeces, changed nutrient inputs) (Figure 12). They also impact chemistry and nutrients via pollution. The degree to which feral carnivores actively hunt in and around peatland areas is unknown, with no literature suggesting that they are highly active in these communities, nor any research on their potential effects. More generally, foxes and cats both hunt and consume birds, small mammals, insects, reptiles and amphibians (McMahon et al. 2015). Consequently, invasive predators are may have population-level impacts on native bog and fen fauna, including frogs (including the critically endangered Northern Corroboree Frogs and the endangered Alpine Tree Frog), fish (*Galaxias* spp.) and crayfish (Wild and Magierowski 2015). They are likely to have a negative impact on small mammals that inhabit the bogs, including the Broad-toothed Rat, and potentially the Rakali (*Hydromys chrysogaster*) in the larger fens on the montane valley floors (ACT Government 2017). Consequently, invasive predators could lead to the loss of or reduction in small vertebrates and ultimately changes in fauna composition (McMahon et al. 2015).

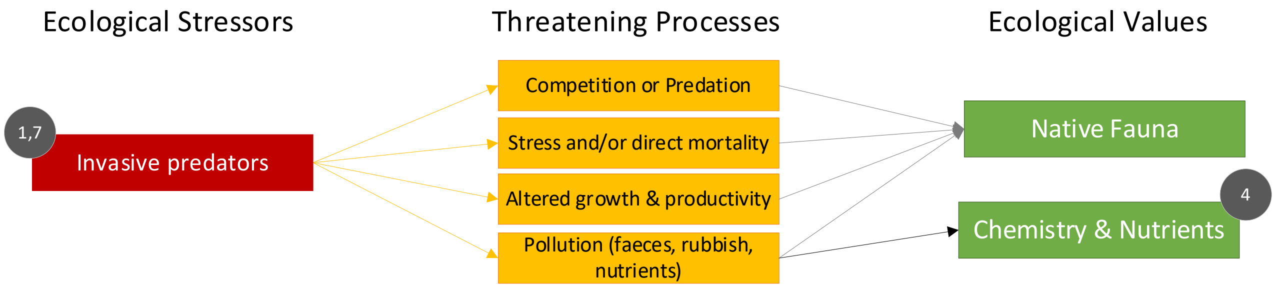

Figure 12 *Subsection of the conceptual model for the bogs and fens focusing on the threatening processes and ecological values that are impacted by invasive predators specifically.*

Potential management actions for invasive predators

There are currently no practical management methods for the control of cats in remote areas around bogs and fens. However, Curiosity™ cat bait uptake trials have recently taken place in Namadgi National Park (ACT Government 2017).

Department of the Environment (2015) suggest that the goal of management should be to minimise the impact of invasive carnivores on the ecological community's fauna. They suggest that actions to eliminate the impacts of invasive predators could include the eradication, containment or control of existing populations of foxes and cats threatening fauna in the ecological community. McMahon et al. (2015) similarly suggests that management actions around invasive predators could include investigating the impacts of dogs, cats and foxes on alpine peatland fauna and, if impacts are significant, control pest species populations to ensure that impacts are limited or reduced to an acceptable level. ACT Government (2017) states that monitoring of invasive predator densities and their impacts on the ecological values of bogs and fens is critical for informing management, where management should be implemented if their densities increase or numbers of key species (including the Broad-toothed Rat) start declining substantially.

Potential indicators for invasive predators

Evidence of the presence/abundance of invasive predators

Evidence of their presence mainly includes the presence of scats, evidence of predation (for example crayfish carcasses and scat analysis) or direct observations (from camera trapping or field surveys).

Evidence of impacts of invasive predators

Evidence of the impacts of invasive predators could include reductions in the numbers of vulnerable species and changes in fauna composition.

Other invasive fauna

Other invasive fauna includes rabbits (*Oryctolagus cuniculus*), hares (*Lepus europaeus)*, alien fish and European wasps (*Vespula germanica)*.

Competition and land degradation by rabbits is listed as a threatening process under the EPBC Act. Department of the Environment (2015) estimate the severity of impacts from rabbits and hares in peatlands to be low, while McMahon et al. (2015) suggests they are likely to have a moderate effect. In Victoria, rabbits have been active to a small extent at the margins of some peatland systems and in the ACT they have been recorded at a number of bogs across as part of a number of different monitoring programs (McMahon et al. 2015). Hares are known to occur in the Snowy Mountains in NSW.

Department of the Environment (2015) estimate the severity of impacts from alien trout to be high. Rainbow Trout (*Oncorhynchus mykiss*) are known to impact galaxias populations, which occur in bogs, and likely aquatic invertebrates as well. Brown (*Salmo trutta*) and rainbow trout are common through lower altitude bogs outside of the Cotter River catchment in the ACT and have resulted in declines or local extinctions of galaxias in these areas (Mathew Beitzel, pers. comm., 2020).

The ACT High Country Bogs and Associated Fens Endangered Ecological Community Draft Action Plan (ACT Government 2022) lists European wasps as an invasive species of significance for bogs and fens as they have been seen in all monitored bogs and nesting in old, dried out *Sphagnum* hummocks (ACT Government 2022). They are recognised as a declared pest within Namadgi National Park (ACT Government 2010). However, European wasps have not been recorded as a threat in other national bogs and fens reports or conservation advice (including, DEWHA 2008, Department of the Environment 2015, McMahon et al. 2015, Wild and Magierowski 2015, ACT Government 2019, Rowland et al. 2023) which suggests that their impacts may be limited, or currently unrecognised. European wasps are thus considered low risk currently, until further research has been completed to better understand their potential impacts on bogs and fens.

Threatening processes of other invasive fauna and impacts on values

Rabbits, hares, alien fish and European wasps can impact all ecological values via 6/17 threatening processes (Figure 13). Digging by rabbits and hares in the areas immediately surrounding bogs and fens can increase erosion, soil disturbance and sedimentation into the endangered community (Milner et al. 2015, ACT Government 2022). They reduce the cover and diversity of forb species in sub-alpine areas, and can change the structure and composition of the habitat (McMahon et al. 2015). Rabbits could impact Broad Toothed Rats through competition and reducing food resources and their effects on the landscape could impact Corroboree Frog habitat (Milner et al. 2015, ACT Government 2022). McMahon et al. (2015) states that no obvious impacts on peatlands from hares have been observed, and the long-term impacts of these animals in high-altitude Australian ecosystems have not been studied. Effects on plant communities are likely to be similar to that from rabbits. Micro-histological examination of faecal pellets from the Snowy Mountains showed that around 9% of the diet of hares in winter consisted of the peatland shrub *Richea continentis*, indicating that hares will enter and utilise peatlands.

Alien fish species both predate on native fish and compete with them for resources such as food and habitat. An incursion of trout could have a major impact on native *Galaxias* species (Department of the Environment 2015). Alien fish also play a role in spreading diseases and parasites through native fish populations (Strayer 2010), and can compromise native macrophyte and invertebrate populations in bogs (Chadderton 2003).

Little is known about the ecological impacts of European wasps in Australia, and no studies have investigated their impacts on the ecological values of bogs and fens specifically, although they are a likely threat to native biodiversity, especially insects and spiders (ACT Government 2010). Introduced vespid wasps are known to cause damage to ecosystems through predation of local invertebrates (Potter-Craven et al. 2018) as well as through competition with local invertebrates for food, influencing the size and morphology of native species or sometimes leading to starvation (Burne et al. 2015). Adult Alpine Sedge-skippers (*Oreisplanus munionga*) are vulnerable to European wasps (ACT Government 2022).

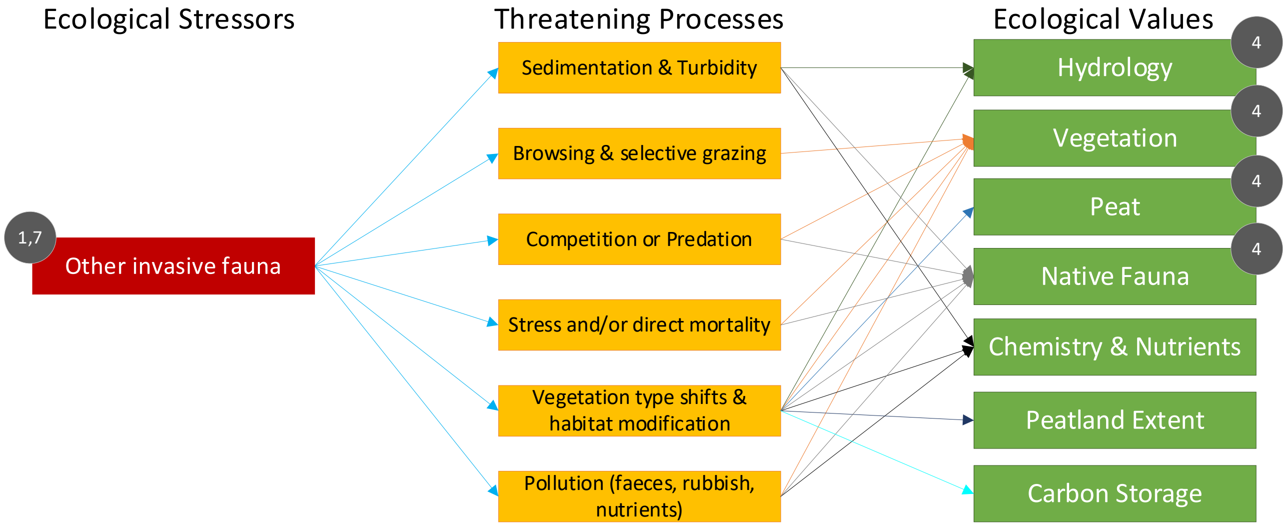

Figure 13 Subsection of the conceptual model for the bogs and fens focusing on the threatening processes and ecological values that are impacted by other invasive fauna (rabbits and hares, alien fish and European wasps) specifically.

Potential Management actions for other invasive fauna and thresholds

McMahon et al. (2015) suggests the key action for rabbits and hares should be to investigate their impacts on alpine peatlands and, if impacts are significant, control populations to ensure that impacts are limited or reduced to an acceptable level. Extensive rabbit management has been undertaken at individual sites (for example the Nursery Swamp valley in the ACT) to reduce the severe impact that large numbers were having on the ecosystem (ACT Government 2022). But aside from this, rabbit management is generally not carried out in or around bogs and fens due to problems with logistics from their remote locations, especially when helicopter access is required because setting traps or leaving baits over days is impractical and inhumane. There is some suggestion that their ecology may be somewhat different in some areas around and in bogs and fens as there has been an observed lack of warrens when rabbits are known to be present. If this is the case, then management methods such as warren fumigation or destruction are not possible (Mark Elford, pers. comm., 2021). It is thought that the main feasible option might be thermal shooting (Mark Elford, pers. comm., 2021).

Alien fish should be prevented from establishing new populations in high altitude streams and water bodies where they do not currently occur. If already established, eradication, containment or control could occur, particularly where galaxiid populations are present or could be re-established (Department of the Environment 2015).

Control of European wasps can include nest destruction and baiting. The Namadgi National Park Plan of Management states that the most effective approach to reducing numbers of this species is likely to be a baiting program at picnic areas (for public safety) and biodiversity hotspots (ACT Government 2010). No current management of European wasps is underway in any bogs and fens in Australia to our knowledge.

Potential Indicators for other invasive fauna

Evidence of the presence/abundance of invasive fauna

Presence of scats, tracks, digging or warrens for rabbits and hares. Estimates of density could potentially be gained from walked transects and counting the numbers of individuals seen, although in other ecosystems this would be done from a vehicle (but is unfeasible in peatlands). The presence and density of alien fish could also be estimated. The presence of wasps or nests could also be used as a potential indicator of presence and abundance.

Evidence of impacts of invasive fauna

Rabbits and hares can impact rates of erosion and soil disturbance, sedimentation, reduce cover and diversity of forbs and impact Broad Toothed Rats and Northern Corroboree Frog presence and abundance. European wasps may impact local invertebrate abundances and composition. Alien fish could impact native Galaxias species presence and abundance, and also native macrophyte and invertebrate populations. It is unclear what the impacts of European wasps are on ecosystem values so until hypotheses are formed about their impacts, indicators measuring these are not feasible.

Weeds

Weeds are consistently recognised as a major threat to bogs and fens. McMahon et al. (2015) ranked woody weeds as having the highest severity rating, followed closely by non-woody weeds. Department of the Environment (2015) ranked both woody and non-woody weeds as very high severity risks to the endangered community. Woody weeds can include both introduced plant species (i.e. high risk weeds) and native dryland woody plants that are not typically found in peatland habitats, usually from lower altitudes (Rowland et al. 2023).

The weeds of highest priority in bogs and fens are those likely to affect hydrological function, particularly the woody weeds, willows (*Salix* spp.) and Blackberry (*Rubus fruticosus*) (Department of the Environment 2015). Non-woody weeds are grassy or herbaceous plants that have been introduced since European colonisation (McMahon et al. 2015). A number of herbaceous weeds currently threaten the Alpine *Sphagnum* Bogs and Associated Fens Ecological Community and in some cases have become widely established (Department of the Environment 2015).

Threatening processes of weeds and impacts on values

Flora and Fauna

Weeds can impact 8/17 threatening processes subsequently affect impact all ecological values (Figure 14). Weeds can compete with natives for space, water and nutrients and can irreversibly change the floristic composition, structure and hydrology (Department of the Environment 2009). Some exotic weeds, such as *Juncus* spp. and willows (*Salix* spp.) have the capacity to establish high densities which could permanently alter the floristic composition of the area (Department of the Environment 2015). Non-woody species can also compete with local species, leading to changes in vegetation composition and structure (McMahon et al. 2015). Ultimately, both woody and non-woody species could cause the loss or reduction of native plant species (McMahon et al. 2015).

Invasions by some weeds, such as Blackberry could alter important frog breeding habitat (ACT Government 2017). Willows and Blackberry could have impacts on in-stream fauna through changes to timing and amount of nutrient input. Non-woody weeds can also degrade important fauna habitat (McMahon et al. 2015).

Hydrology

The invasion of woody weeds can signal a shift in the underlying hydrology and health of the system. For instance, Scheele et al. (2012) measured recent tree invasion in bogs (the number of trees under 5 cm diameter at breast height) as the measure is indicative of site drying and suggests reduced moisture availability. In support of this measure, they found that the probability of Northern Corroboree Frog occurrence at extant sites compared with extinction sites was negatively related to tree invasion. Some species, particularly willows, have the capacity to alter the structure and hydrology of peatlands due to their deep, dense root mats, high water use and seasonal leaf drop (McMahon et al. 2015).

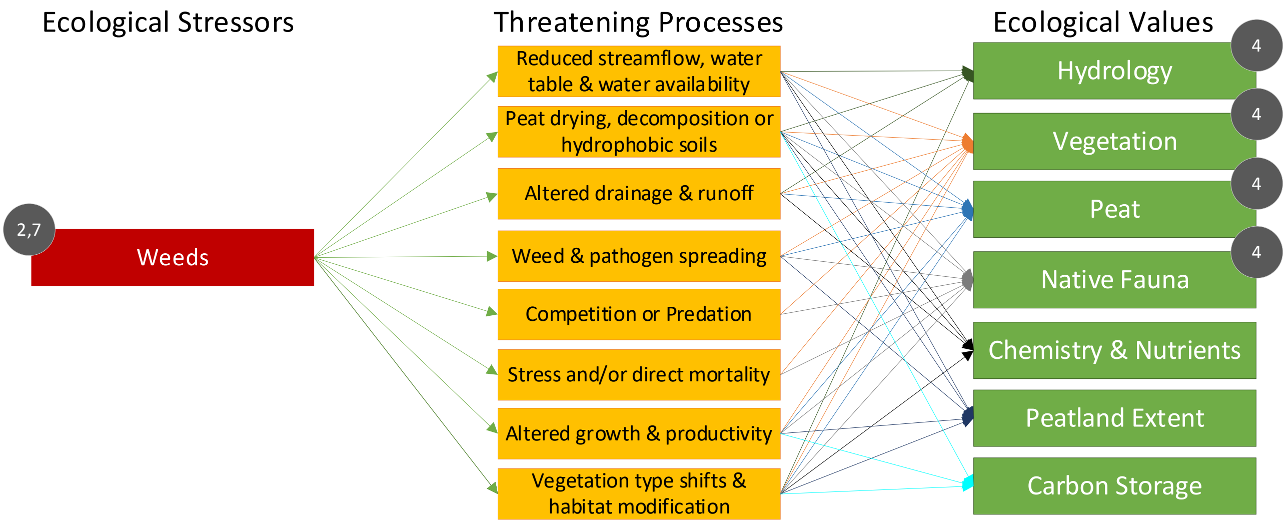

Figure 14 *Subsection of the conceptual model for the bogs and fens focusing on the threatening processes and ecological values that are impacted by weeds (woody and non-woody) specifically.*

Potential management actions for weeds

Macdonald (2009) recommended that formal programs to monitor and remove all invasive weeds (both introduced species and encroaching dry-land species) in the *Sphagnum* bogs and their surrounds need to be established and maintained. A program such as this would likely include felling woody trees that are encroaching and removing invasive species (Bonnett et al. 2009). However, the inaccessibility and remoteness of many sites and the nature of these threats will pose a challenge for weed detection, prevention, management and eradication (Threatened Species Scientific Committee 2009). Additionally, the sensitivity of bogs and fens to chemicals makes effective weed control challenging (Department of the Environment 2015).

Strict protocols should be in place for anyone entering the community. Most non-woody weeds have been introduced unintentionally, through seed attached to vehicles, humans and animals (McMahon et al. 2015). Consequently, strict vehicle washing and sanitation procedures are an important management process.

DEWHA (2008) suggest that management should aim for weeds in bogs and fens to be eradicated or at least controlled within the ecological community using appropriate methods. Management is especially important at sites where emerging threats (e.g. *Salix* spp. willows) are not yet established to prevent them becoming a threat. McMahon et al. (2015) suggests that control of priority woody weeds threatening alpine peatlands should aim to: 1) reduce or limit their impacts to an acceptable level; 2) contain localised infestations to prevent spread; 3) eliminate isolated infestations where practicable; and 4) prevent establishment of new infestations in areas where particular species do not presently occur. This will involve working with different land managers to control the main sources of seed.

Potential indicators for weeds

Evidence of presence and density of weeds

Evidence of the presence and density of weeds can include measuring weed density (e.g. plants per km) or the percent cover of weeds in quadrats or transects. Woody trees can be measured as the number of trees under 5 cm diameter at breast height at the site (Scheele et al. 2012).

Management of woody weeds should be targeted at those expected to be most invasive and have the greatest impacts. For instance, several woody weeds are listed as Weeds of National Significance due to their high capacity to invade and impact recipient communities, including willows (particularly *Salix cinerea,* Grey Sallow Willow which is considered the most highly invasive), Blackberry (*Rubus fruticosus)* and English Broom *(Cytisus scoparius)* (Threatened Species Scientific Committee 2009, McMahon et al. 2015).

The non-woody weed *Juncus effusus* is now highly established in some previously grazed areas in Victoria and has permanently altered the floristic composition and vegetative structure of some bog and fen sites (Department of the Environment 2015). *Eragrostis curvula* (African love-grass) has been recently discovered in several high altitude bogs in the ACT (Department of the Environment 2015). Some non-woody weeds are widespread and common, to the extent that they are almost ubiquitous in peatlands in some areas in Australia, including *Holcus lanatus* (Yorkshire Fog), *Trifolium repens* (White Clover) and *Anthoxanthum odoratum* (Sweet Vernal-grass). Other non-woody weeds of potential concern for bogs and fens across Australia include *Mimulus moschatus* (Musk Monkey Flower), *Phleum pratense* (Timothy Grass), *Holcus lanatus* (Yorkshire Fog), and *Hypochoeris radicata* (Cat's Ear), *Juncus effusus* (Soft Rush), *Acetosella vulgaris* (Sheep Sorrel), *Taraxacum officinale* (Garden Dandelion), *Hypochoeris radicata* (Flatweed or Cat's Ear), *Lotus uliginosus* (birds-foot trefoil), *Agrostis capillaris* (creeping bent grass), *Glyceria maxima* (reed sweet grass), *Phalaris arundinacea* (reed canary grass), *Juncus articulatus* (jointed rush), *Leucanthemum vulgare* (ox-eye daisy), *Myosotis laxa subsp. caespitosa* (water forget-me-not), and *Poa annua* (annual meadow grass) (Department of the Environment 2009, Threatened Species Scientific Committee 2009, Department of the Environment 2015, McMahon et al. 2015, Wild and Magierowski 2015).

Evidence of impacts of weeds

Evidence of the impacts of weeds could include measuring changes in vegetation composition and structure or declines in local native species densities. Changes to abundance of frogs and in-stream fauna. Changes in water table, soil moisture and peat structure.

Pathogens and disease

Pathogens include fungi and other diseases potentially impacting on peatland values (McMahon et al. 2015). Pathogens and diseases such as *Chytrid* fungus, *Phytophthora*, myrtle rust, didymo and Epizootic Haematopoietic Necrosis Virus are unpredictable in when and where they might appear making them difficult to manage. They are classified as having a very high national severity rating (Department of the Environment 2015), and as the highest severity category in McMahon et al. (2015).

Threatening processes and impacts on values

Pathogens and disease impact all ecological values via 5/17 threatening processes (Figure 15). Ultimately, the whole bog and fen community could be impacted if the ecological function of the system is impaired through loss of key species (McMahon et al. 2015). *Chytrid* fungus is a known pathogen causing the disease *Chytridiomycosis* in frogs and has been listed under the EPBC Act as a Key Threatening Process contributing to the decline in Australian frog species. *Chytrid* in bogs and fens has already resulted in drastic declines of the Northern Corroboree Frog in the ACT and is known to impact other species such as the Alpine Tree Frog (Hunter et al. 2010, Department of the Environment 2015).

The fungal pathogen *Phytophthora* affects plants across a range of Australian ecosystems and is considered likely to emerge in bog and fen communities. It's recently been linked to dieback in the alpine area of Kosciuszko National Park, impacting the dryland alpine shrub *Nematolepis ovatifolia* in the Snowy Mountains of NSW, and at least 11 different species of this pathogen have been detected in soils within Kosciuszko National Park (Department of the Environment 2015, McMahon et al. 2015). Common peatland shrub species from the genus' *Epacris* and *Richea* have been shown to be highly susceptible to the pathogen (McMahon et al. 2015).

Fish in bogs and fens could potentially be impacted by the Epizootic Haematopoietic Necrosis Virus (EHNV) which causes mortality in threatened fish species (ACT Government 2017), or Didymo (a highly invasive algae) which currently doesn't occur in Australia but is a significant problem in New Zealand (Department of the Environment 2015).

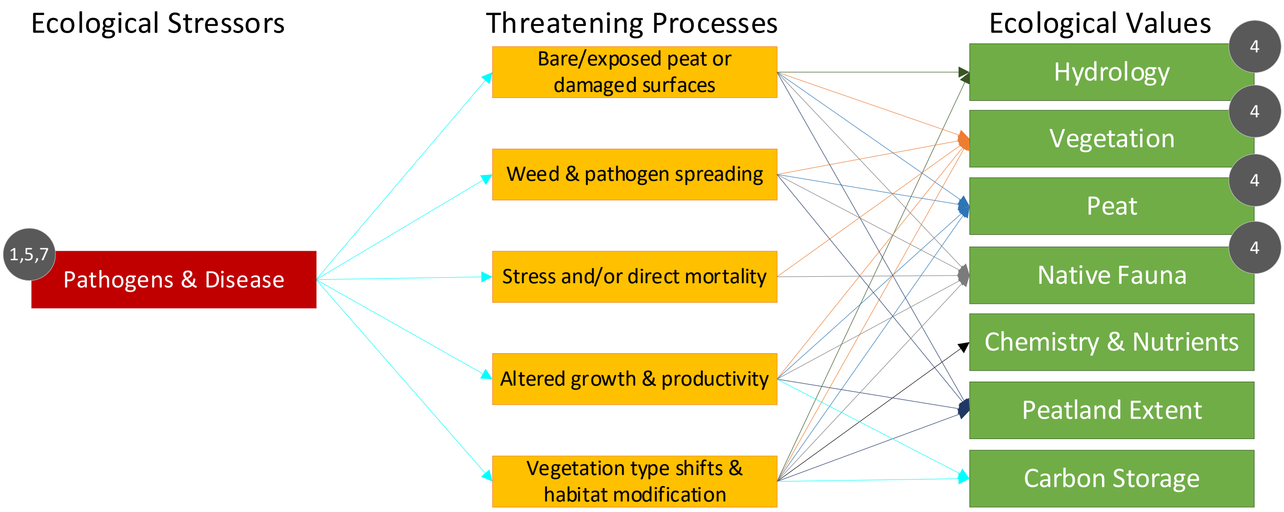

Figure 15 *Subsection of the Conceptual model for the bogs and fens focusing on the threatening processes and ecological values that are impacted by pathogens and disease specifically.*

Potential management actions for pathogens and disease and thresholds

Containment or control of a pathogenic infestation in isolation is always likely to be difficult, but is recommended given the consequences of a pathogenic outbreak in combination with other threats could be very high (Department of the Environment 2015). However, it is acknowledged that little is known about how to control pathogens such as *Chytrid* fungus (McMahon et al. 2015). Department of the Environment (2015) suggests that management actions should aim to minimise the impacts of pathogens/diseases on the ecological community. Specifically, actions can include (1) continuing vigilance for new disease outbreaks and emerging threats by developing field capability in land management staff, public and private landholders in identifying diseases likely to threaten the ecological community, and (2) where possible, identifying, preventing, eradicating, containing or controlling pathogens and diseases where they threaten the ecological community. The choice of how to manage pathogens or diseases will need to be informed by first understanding its extent in an area to determine prioritisation of management funds and the appropriate management method (Commonwealth of Australia 2018).

Currently, strict protocols should be in place for anyone entering these communities. One of the best preventative measures is to ensure that field staff employ best-practice hygiene protocols to minimise the risk of spread of pathogens. For instance, humans can spread *Phytophthora* further and faster than any other infestation vector. Any activity that moves soil, organic material or water into susceptible native vegetation areas has the potential to introduce and spread soil pathogens. The limited management options available focus on modifying human activities through education, restricting access to certain sites and, when access is necessary, deploying and enforcing stringent hygiene protocols before entering or leaving a site to minimise the spread of Phytophthora in the landscape (Commonwealth of Australia 2018). Another option is for recreational visitation to be discouraged.

Actions to address the pathogen or disease directly may also sometimes be available. For instance, the strategic application of phosphite has been shown to reduce the rate of autonomous spread of *Phytophthora*, enhance the survival of susceptible species and ameliorate impacts on plant community structure. Yet, such an option for others, such as *Chytrid* fungus do not currently exist.

Potential indicators for pathogens and disease

Evidence of presence of pathogens or disease

Presence sampling (e.g. soils) or evidence of impacts.

Evidence of impacts of pathogens or disease

Decline in susceptible fauna (particularly amphibians) and susceptible plants. Potential impairment of ecological function through loss of species.

Recreation

Recreational use can include a variety of off-track activities, including hiking, cross-country skiing, mountain bike riding, off-track vehicle use, and hunting and fishing – not all of which are legal activities (McMahon et al. 2015). *Sphagnum* bogs are fragile and even low levels of visitor use can have significant impacts (ACT Government 2017). Off-track recreation is ranked as a medium severity rating by both Department of the Environment (2015) and McMahon et al. (2015)

Threatening processes of recreation and impacts on values

Recreation impacts all ecological values via 5/17 threatening processes (Figure 16). Although the impacts of recreation are typically localised, visitors can cause a range of threatening processes which can cause declines in ecological values. Impacts can include trampling of *Sphagnum* moss and spreading of weed seed and pathogens. Trampling in sensitive vegetation such as *Sphagnum* moss will have significant impact after only 30 passes, and recovery from that level of impact will take 3–5 years (Whinam et al. 2003b, ACT Government 2017). Walkers are responsible for spreading a significant amount of weed seeds in Kosciusko National Park (ACT Government 2017). Of greatest concern is illegal off-track vehicle use or old vehicle tracks which can cause substantial, long-lasting damage to peatlands (McMahon et al. 2015). If visitor use reaches high numbers, tracks through peatlands could then become more entrenched, channelling water away. Other impacts can include a decline in water quality, erosion and sediment deposition, conversion of peatlands to drier vegetation types and damage to fauna habitat (McMahon et al. 2015).

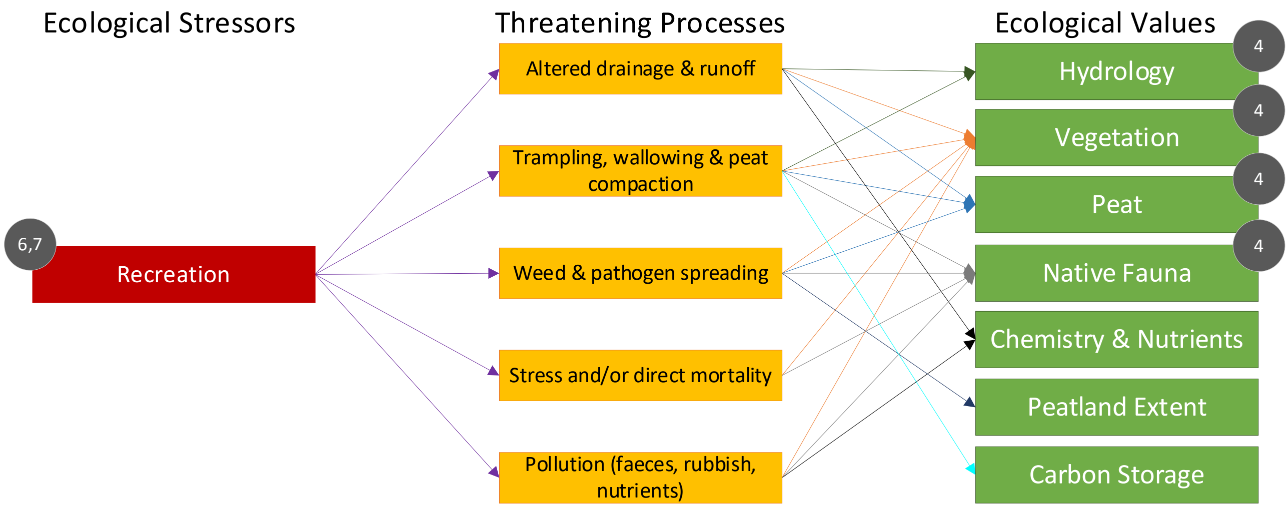

Figure 16 Subsection of the Conceptual model for the bogs and fens focusing on the threatening processes and ecological values that are impacted by pathogens and disease specifically.

Potential management actions for recreation and thresholds

Management to reduce the impacts of recreation in bogs and fens currently includes several options. Management of visitor impacts on the bogs can be achieved through education (including signs), avoiding directing people into bog areas and removing (or not maintaining) access tracks to bogs and enforcement to manage illegal actions. The use of permits to carry out research or search and rescue exercises and orienteering and rogaining events is another option.

Department of the Environment (2015) suggests the management goal “avoid and minimise impacts of recreational activities” where actions can include ensuring that permitted off-track recreational activities do not impact the ecological community and the impacts of illegal or inappropriate off-track use are mitigated by managing sites to prevent access and rehabilitating damaged sites. McMahon et al. (2015) states that the first management actions should be to identify off-track recreational use and implement actions to mitigate their impacts. For instance, if recreation becomes a problem, fencing can be used to protect individual peatlands from off-track recreational impacts but is an expensive solution, particularly in locations that are distant from road access.

Potential indicators for recreation

Evidence of presence of recreational activities

Evidence of the presence of recreational activities can include identifying areas within or nearby bogs and fens that are affected by off-track recreational use, including the number of unofficial walking trails, but also illegal vehicle driving.

Evidence of impacts of recreational activities

Evidence of impacts from recreational activities can include changes to drainage, channels and hydrology, health of sensitive plants such as *Sphagnum*, water quality, rates or erosions and sedimentation and change in vegetation community composition.

Infrastructure and development

Infrastructure and development can include tracks and roads, water infrastructure (including aqueducts, hydro developments) and resort development. Department of the Environment (2015) ranked the national severity rating for these threats as very high for water infrastructure, high for resort development and medium for tracks and roads, while McMahon et al. (2015) ranked them all equally high severity.

Threatening processes of infrastructure and development and impacts on values

Infrastructure and development impacts all ecological values via 6/17 threatening processes (Figure 17). For instance, existing, development and/or use of infrastructure such as roads has the potential to impact the ecological character of the wetland through altered hydrology (increased runoff) and changes to water quality (for example increased sediments and turbidity, introduction of pollutants such as oil (Wild et al. 2010). Such impacts have the potential to impact peat formation, vegetation and habitat availability within the wetland.

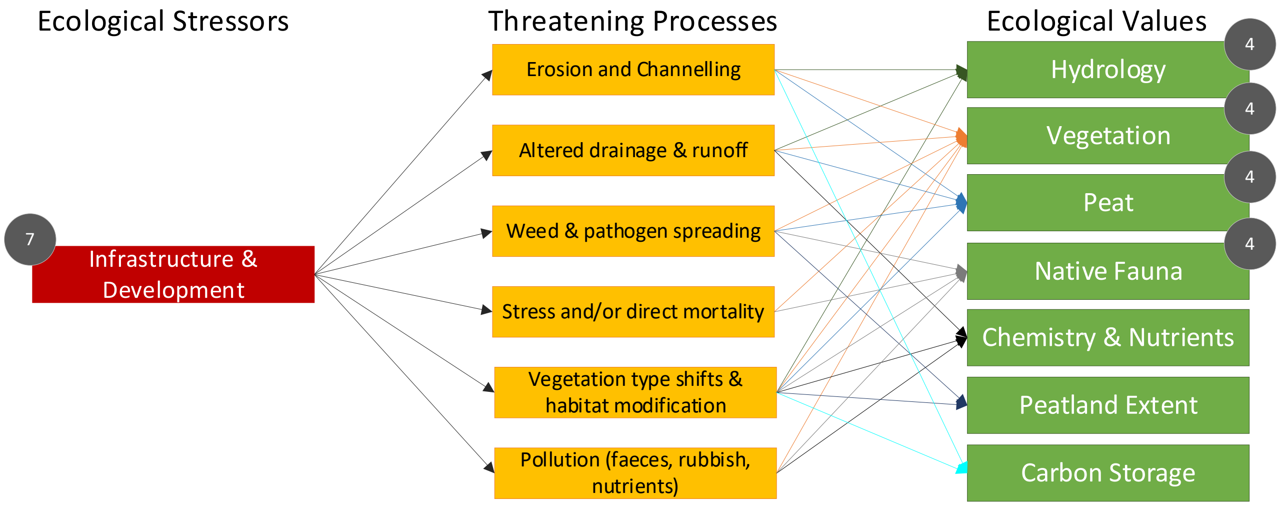

Figure 17 Subsection of the conceptual model for the bogs and fens focusing on the threatening processes and ecological values that are impacted by pathogens and disease specifically.

Potential management actions for infrastructure and development and thresholds

Areas with infrastructure or development should determine which bogs and fens are potentially impacted and examine what actions could be taken to improve the integrity and functioning, including improved vegetation management and erosion control. Additionally, proposals for new or altered infrastructure should consider and protect the structural and hydrological integrity of those bogs and fens (McMahon et al. 2015).

Potential indicators for infrastructure and development

Evidence of presence of infrastructure and development

Presence and type of infrastructure and development and distance from bog and fen sites.

Evidence of impacts from infrastructure and development

Evidence of impacts from infrastructure and development can include hydrological changes such as altered runoff, water quality, sedimentation and turbidity, as well as the presence of pollutants (e.g. oil), lowered rates of peat formation and changes to vegetation structure and composition.

Resource Use

Resource use could include peat and *Sphagnum* harvesting, timber harvesting and groundwater extraction. At a national scale, the rated severity is very high for peat and *Sphagnum* harvesting, and medium for timber harvesting and groundwater extraction (Department of the Environment 2015, McMahon et al. 2015). For instance, *Sphagnum* harvesting is a prominent issue in Tasmania (DEWHA 2008). There is currently little known about potential cultural resource use.

Threatening processes of resource use and impacts on values

Resource use impacts all ecological values via 9/17 threatening processes (Figure 18). Peat harvesting can have large and severe immediate impacts including the immediate removal of vegetation, exposure of peat, mechanical damage by harvesting equipment, drainage leading to drying of the peatland, degradation of fauna habitat, increased erosion and sedimentation and increased susceptibility to the effects of fire, ultimately leading to changes in the structure and hydrology of peatlands (McMahon et al. 2015). *Sphagnum* is a resource used by the horticulture industry, and in the early 1990s around 15 tonnes per year were harvested in Tasmania, and a small amount in Victoria. *Sphagnum* regeneration on the bare peat surface remaining after complete harvesting is slow, or sometimes absent, leading to dominance by other species such as rushes and sedges (Whinam and Buxton 1997). The impacts of timber harvesting and groundwater extraction are not known. However, timber harvesting, particularly of high-elevation Ash forests, could impact on the hydrology and structure of nearby peatlands. Groundwater extraction potentially reduces the amount of water that can flow out through peatlands which could impact vegetation growth and composition (McMahon et al. 2015). However, any activities in the headwaters, such as logging, can alter water quality and hence the ecology of the peatlands (Whinam and Buxton 1997).

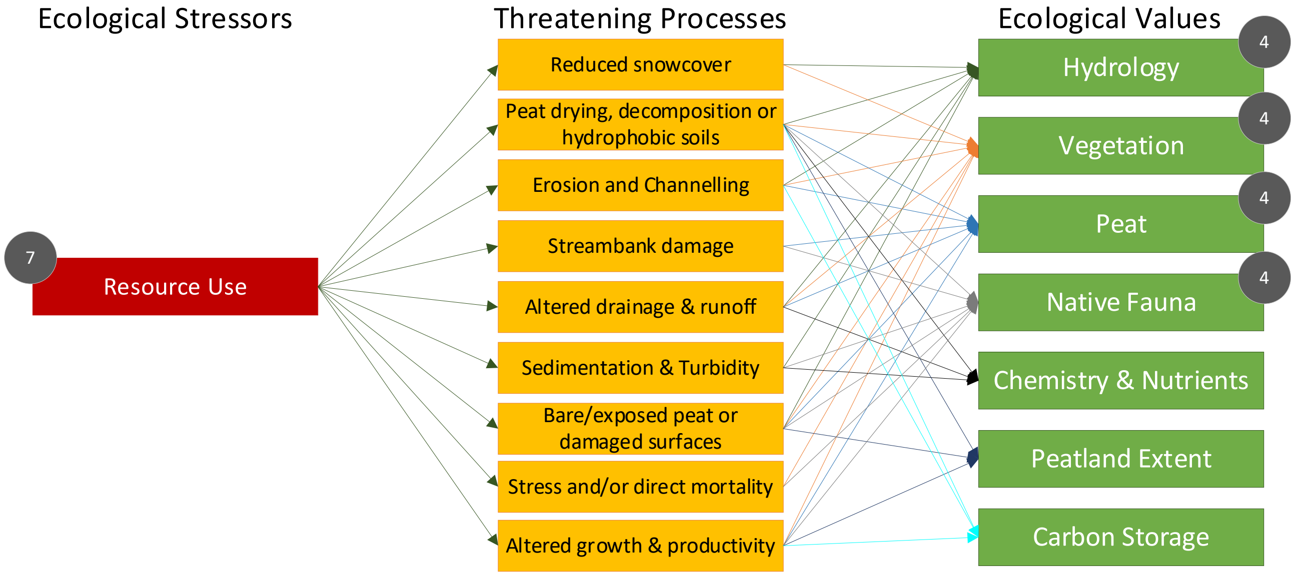

Figure 18 *Subsection of the conceptual model for the bogs and fens focusing on the threatening processes and ecological values that are impacted by resource use specifically.*

Potential management actions for resource use and thresholds

Department of the Environment (2015) suggest two main management goals around resource use, (1) avoid impacts from resource use (e.g. peat, *Sphagnum* and timber harvesting, groundwater extraction), and mitigate past impacts, where possible, and (2) increase compliance and enforcement for illegal resource use. Specifically, achieving this could include preventing new resource use that will damage the ecological community within national parks, minimising the impacts of resource use where it has previously occurred, improving surveillance and compliance for illegal resource use and ensuring that appropriate penalties are applied for illegal activities that damage the ecological community.

Potential indicators for resource use

Evidence of presence of resource use

Evidence of the presence of illegal resource use could be collected from surveillance at key sites.

Evidence of impacts of resource use

Changes to drainage and hydrology, bare ground, erosion and sedimentation, decreased vegetation cover.

Primary Drivers

The condition of bogs and fens will also be the result of other factors independent of stressors and threatening processes, and outside the influence of contemporary management actions. These primary drivers need to be taken into account when understanding the condition of the community today. Some drivers are environmental, such as climate and topography, while others are anthropogenic, such as land-use history (e.g., grazing). Identifying, and accounting for, primary drivers that can influence ecological values like vegetation composition or hydrology is important when assessing the condition of bogs or comparing condition across sites. For example, it could be the case that management targets might need to be adjusted if it is unrealistic or too costly to aim for the same condition targets in untouched sites versus sites with long grazing, fire and land use histories that have substantially degraded them over time. Future research should therefore take factors such as these into consideration wherever possible when considering site selection for research or management evaluation, and whether these factors can be quantitatively accounted for in statistical analyses.

Grazing History

One of the better documented threats to alpine vegetation is the impact of grazing since European colonisation. Although cattle no longer have legal access to national parks, it is important to understand that the impact of non-native animals on alpine vegetation is long-term, with the effects remaining long after the initial problem is removed (Department of the Environment 2009).

Fire History

Fire has been a feature of the montane and subalpine landscape, and the bogs and fens have not been immune from its impacts. Wildfires that may have had an impact on the bogs and fens in the Australian Alps in post-European times occurred in 1851, 1875, 1899, 1918, 1925, 1939, 1944, 1983, 2003 and 2020. Prior to this, major fires were less frequent and likely to have occurred approximately every 50 years (Banks 1989, Macdonald 2009).

Past Land Use

Past land use could include several types of impacts. Nearby plantations or arboreta can influence weeds in peatlands. For instance, escaped exotic species from the arboreta established in the Brindabella ranges in the 1930s have managed to establish seedlings in peatlands (Macdonald 2009). Resource use, such as trench digging, peat extraction or *Sphagnum* mining can also have long lasting effects. For instance, *Sphagnum* mining for use in filters in vehicle gas producers occurred during World War II. These areas have been suggested to recover significantly slower than unmined areas (Macdonald 2009).

Climate and topography

For peatlands to form, several specific climatic and topographic features are required. Almost all peatlands in Australia occupy low places in the landscape (i.e. alpine valley sites), and are termed topogenous mires (caused by topography). This is because for organic matter to accumulate, the conditions must be cool and wet, with permanent inflows of water to maintain waterlogged conditions. Consequently, peatlands may form in wet, cool montane areas in low gradient valleys, while near the alpine treeline these valley sites may extend onto gentle slopes to form *ombrogenous* (formed by cloud) blanket bog (Hope 2003). The floristic composition of *Sphagnum* bogs in Victoria has been found to be related to climate and altitude (Whinam et al. 2003a).

Geology

The geology of bogs and fens determines the water-holding capacity of the rock substrate, as well as the porosity of the soils. For example, the best-developed bogs in Victoria are those on metamorphic substrates on the Bogong High Plains, where they form big systems along seepage lines on gentle slopes. In contrast, bogs at Buffalo tend to be in lower parts of the landscape with a rectilinear drainage pattern that reflects the granite geology. The soils are also very gravelly, so the bogs are less defined on slopes (Arn

Tolsma, pers. comm., 2021). The floristic composition of *Sphagnum* bogs in Victoria has been found to be related to geology (Whinam et al. 2003a).

Prioritisation of Indicators

Because it is difficult to monitor every aspect identified in the conceptual model (Figure **1**), there is a need to prioritise those that are most important for describing condition and functioning, understanding why change may be occurring over time, and informing management. This prioritisation process is critical for understanding which ecosystem components are important indicators of ecosystem health, on which to base decisions around long-term monitoring for future programs. To our knowledge, the prioritisation of ecological values and threatening processes has not previously been carried out in the published literature.

We have suggested indicators that could be used to reflect the status of the ecological values and stressors based on the Review of Key Bog and Fen Components. These are all indicators that we consider could be achievable for long-term monitoring of bogs and fens, and have recently been taken up as part of the ACT Government's bogs and fens condition assessment as part of the Conservation Effectiveness Monitoring Program (CEMP) (McLean et al. 2023a). We then prioritised them based on expert knowledge.

Here, prioritisation is purely based on the perceived importance of an indicator to the health and condition of bogs and fens. Issues surrounding practicalities around monitoring indicators (e.g. costs, expertise required, time needed) have not been taken into consideration, but would be a necessary consideration if specific variables were being considered during the development of long-term research and monitoring programs.

To carry out this process, we asked twelve experts to categorise the usefulness of values as an indicator for peatland health, functioning or condition as either critical, high, moderate, low or unknown. We then averaged responses across the six expert responses that were received by converting scores into numbers (critical = 4, high = 3, moderate = 2 and low = 1). Where averaged scores were within 0.25 of the next category they were rounded to the closest category, otherwise they were prioritised as between two categories (i.e. Moderate – High). For the threatening processes, we asked what was the threatening processes' likely strength of impact on peatland condition and function. The choices included a strong impact (score of 3), moderate (score of 2), weak (score of 1) or unknown.

Table 3 *The priority of indicators for each ecological value were determined by six experts in the field of bogs and fens. The priority of indicators is based on how useful they were considered to be as an indicator for peatland health, functioning or condition. Indicators were categorised as Critical, High, Moderate or Low.*

Values	Indicator	Priority
Hydrology	Water table & holding capacity	High - Critical
Hydrology	Soil & surface moisture availability	High
Peatland area	Extent of bog or fen area	High
Chemistry and nutrients	Chemistry, nutrients and water quality	High

Values	Indicator	Priority
Vegetation	Vegetation structure	High
Vegetation	Sphagnum moss	High (for Sphagnum bogs only)
Vegetation	Vegetation composition	Moderate - High
Carbon storage	Carbon storage	Moderate
Peat substratum	Peat substratum	Moderate
Native Fauna	Characteristic/Keystone Native Fauna	Moderate
Vegetation	Threatened species: Endangered orchids	Low - Moderate
Native Fauna	Threatened fauna	Low - Moderate

The indicators for the values hydrology, peatland area/extent, chemistry and nutrients and vegetation tended to be given the highest priority scores across the experts, suggesting that these factors are critical to understanding the health of bogs (Table 3). However, experts noted that although hydrology is critical for informing the condition of bogs and fens, there are issues with a lack of current baseline information on what good condition would look like or how best to monitor it. Native fauna and threatened flora were considered to be the lowest priorities for indicating the health and condition of peatlands. Some comments from the experts suggested that this could be because, although presence of key or threatened fauna can indicate a healthy system, absence may not necessarily be an indicator of poor condition. There can also be issues with collecting enough data of rare species to be of use. It's worth noting that the experts scores for carbon storage and peat substratum varied substantially from scores of low to critical, such that the averaged priority cancelled out to be moderate.

The highest priority threatening processes were around reduced water in the system, drying or damaged peat soils and changes in shifts in vegetation types such that the habitat is modified as they were believed to have the strongest impacts on peatland condition. Threats that were likely to have a moderate to strong impact included most of the other peat or hydrological processes, including erosion and channelling, changes to drainage and runoff and nutrient changes. Trampling, wallows and peat compaction, and stress or mortality of vegetation were also considered as having moderate to strong impacts.

Threatening processes with moderate impacts likely linked with climate change included reduced snowcover, *Sphagnum* bleaching, and carbon source (as opposed to sink). The likely strength of impacts of the process 'carbon source (as opposed to sink) was mostly unknown across the experts, but was noted that the loss of carbon means loss of peat soil that is likely related to changes in hydrology. Many experts noted that their classification for the threatening process 'weed and pathogen spreading' would differ depending on the specific example or species. In particular, several experts noted that the impact would be strong for pathogens and weak for weeds. Consequently, the score varied substantially across the experts. Finally many of the threatening processes caused by pests and fire were also considered moderate impacts, such as streambank damage, browsing and selective grazing, and altered growth and productivity of vegetation. Many of the threatening processes considered to have a weak to moderate impact were around changes in stress, mortality and productivity of fauna. Lastly, pollution was believed to have a weak impact on bog condition.

Table 4 *The priority of threatening processes were determined by six experts in the field of bogs and fens. The priority of each threatening process is based on the likely strength of impact on peatland condition and functioning. Indicators were categorised as having strong impacts were considered high priority, moderate impacts as moderate priority and weak impacts as low priority.*

Threatening Processes	**Likely strength of impact on peatland condition and functioning**
Reduced streamflow, water table & water availability	Strong
Peat drying, decomposition or hydrophobic soils	Strong
Bare/exposed peat or damaged surfaces	Strong
Vegetation type shifts & habitat modification	Strong
Erosion and channelling	Moderate - Strong
Altered drainage & runoff	Moderate - Strong
Trampling, wallowing & peat compaction	Moderate - Strong
Stress and/or direct mortality of vegetation	Moderate - Strong
Altered nutrient input	Moderate - Strong
Reduced snow cover	Moderate
Streambank damage	Moderate
Browsing & selective grazing (by pests)	Moderate
Sphagnum bleaching	Moderate
Altered growth & productivity of vegetation	Moderate
Carbon source (as opposed to sink)	Moderate
Weed & pathogen spreading	Moderate
Sedimentation & turbidity	Weak - Moderate
Competition or predation (with invasive species)	Weak - Moderate
Stress and/or direct mortality of fauna	Weak - Moderate
Altered growth & productivity of fauna	Weak - Moderate
Pollution (faeces, rubbish)	Weak

The prioritising of stressors was based on the assessments of severity already made by McMahon et al. (2015) and Department of the Environment (2015) (Table 5). More information on these prioritisations can be found under the Review of Key Bog and Fen Components section for each of the stressors.

Table 5 Each metric has been prioritised as either low, moderate, high or very high based on McMahon, Tolsma et al. (2015) and Department of the Environment (2015).

Stressor	Indicator	Priority
Climate change	Climate Change	Very High
Fire	Fire	Very High
Pathogens and disease	Pathogens and disease	Very High
Weeds	Woody weeds	Very High
Invasive hard-hooved animals	Horses	Very High
Invasive hard-hooved animals	Domestic livestock	Very High
Resource Use	Peat and *Sphagnum* harvesting	Very High
Weeds	Non-woody weeds	High
Other invasive fauna	Alien Fish	High
Invasive hard-hooved animals	Pigs	High
Invasive hard-hooved animals	Deer	High
Infrastructure and Development	Tracks and roads	Moderate - High
Invasive predators	Cats	Moderate
Invasive predators	Foxes	Moderate

Conclusion

This report represents the conceptual synthesis of ecological knowledge needed to properly identify, plan, and develop new processes to achieve robust evidence-based adaptive management of peatland ecosystems. Consequently, it can be used to guide the establishment of long-term condition monitoring and to inform what management might be effectively linked to each of the ecosystem values and stressors for bogs and fens in Australia.

The development of conceptual ecosystem models for peatlands creates a consistent, quantifiable, and systematic approach for representing shared understanding, identifying knowledge gaps, and prioritising investment. Having these models helps ensure that management and monitoring is strongly linked to policy and decision-making with a focus on delivering the vision for nature conservation. Conceptual ecosystem models contribute to whole-of-government transparency and accountability by making *a priori* predictions and expectations.

This is a first attempt to identify the key ecological stressors, threatening processes and ecological values that can be considered when determining the overall condition of bogs and fens in Australia. As we learn more about these ecological components and their linkages, they should be adjusted through an adaptive approach in the future.

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