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Flatback futures — scenarios and adaptation pathways for a marine turtle facing long-term change

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ABSTRACT: Australia's endemic flatback turtle *Natator depressus* is the focus of a 60 yr conservation program aimed at securing the long-term persistence of healthy populations in the northwest of Australia. In this region, climate change and industrial development are changing the conditions in which flatback turtles live. These conditions are moving outside the historical bounds for the system, and changes are projected to continue for many decades, which necessitates a long-term view in conservation planning. Here, we developed illustrative scenarios spanning a range of plausible biological and socio-economic futures for flatback turtles in which the intensity of climate change and development vary. Scenarios were then used to draft adaptation pathways that allow consideration of alternative conservation management and policy options, show the lead times needed to develop these options, and set out near-term actions to help managers choose and implement such options, if and when needed. While the future trajectory of change is uncertain, these approaches can be used to future-proof thinking for conservation managers, integrating near-term and long-term imperatives, and should be used widely for improved outcomes in natural systems where human impacts are likely. While our study is focused on flatback turtles in northwest Australia, the approach presented here can also be applied to support future thinking and planning to support the conservation of other protected species.

KEY WORDS: Climate change · Flatback turtle · *Natator depressus* · Foresighting · Coastal development · Intervention

1. INTRODUCTION

Conservation attention has long been directed at reducing threats to species and habitats, with the assumption that with those threats reduced, the outcome will be positive. In an equilibrium world, such assumptions were plausible. However, it is now apparent that in many regions, species and habitats face long-term directional change due to climate change and human population growth which renders such approaches inadequate (Halpern et al. 2019, Abbass et al. 2022). Projections for both population growth and climate change suggest that these pressures will continue to 2050, and beyond (IPCC 2021). Navigating a long-term future is thus complicated for conservation managers charged with the management and protection of many species and habitats.

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The above is particularly pertinent for the flatback turtle *Natator depressus*, with all known breeding sites occurring in Australia (Pendoley et al. 2014). Flatback turtles nest in summer or winter on inshore islands and on the mainland from Mon Repos in southern Queensland, around the north coast of Australia to Exmouth in northern Western Australia, and are divided into 7 stocks (FitzSimmons et al. 2020). The population status of flatback turtles is under threat from a range of impacts associated with artificial light, predation from introduced animals, climate change, and marine debris, among others (NWSFTCP 2014). Flatback turtles are listed as vulnerable under the Australian Commonwealth Environment Protection and Biodiversity Conservation Act 1999.

In this paper we focus on the summer-nesting North West Shelf stock of flatback turtles within the Pilbara region of northwestern Australia, which have a nesting range between Port Hedland and the Exmouth Gulf (NWSFTCP 2014). This is an area of rapid industrial development and economic growth due to marine (e.g. oil and gas) and terrestrial (e.g. iron ore) resource extraction. Townships within this region (e.g. Port Hedland) and adjacent islands that contain rookeries are highly industrialised with known impacts on flatbacks from shoreline erosion and artificial light, and likely impacts from pollution and recreational activities (NWSFTCP 2014, van Putten et al. 2023). Towns in this region can host a dynamic workforce (fly-in fly-out workers employed in mining) that seeks a range of recreational marine activities and may be unaware of some of the vulnerable species native to the region, including flatback turtles. Fortunately, flatback turtles in this region are the subject of a long-term conservation program funded by industry as an offset to oil and gas development. The North West Shelf Flatback Turtle Conservation Program (NWSFTCP) is a 60 yr program that aims to conserve the North West Shelf flatback stock. This program provides motivation for conservation managers to consider both short and long time scales and can serve as a model for other species and regions.

Given the long-term focus of the NWSFTCP, conservation managers require tools and strategies that allow for anticipatory and forward planning (Boyd et al. 2015). In considering long term outcomes under uncertainty, scenarios can be used to provide a basis for exploring the future (Costanza et al. 2011, Hobday et al. 2020, Kelly et al. 2022). Scenarios are essentially stories and/or narratives that consider how alternative probable futures may arise from combinations of drivers (Wyborn et al. 2020). Scenario-based work is thus less prescriptive than model-based descriptions of likely futures; however, scenarios are best suited to exploring situations of high uncertainty and low controllability, and they can be used to explore uncertainties in the drivers of change, dynamics of a system, or management responses to change (Costanza et al. 2011, Kelly et al. 2022).

In the case of flatback turtles, scenarios may provide an understanding of the range of fates of the turtle population over the long term, focussing on what might be observed in the far future, even when the causes of change might be unclear. Scenarios can help elicit understanding about the types of novel decisions that managers might face in the future, and inform the new data, management options, and policy and stakeholder engagement needed to make those decisions effectively. Scenarios can also allow a 'future test' of current plans and use of multiple scenarios can help with future planning that must negotiate this uncertainty.

Scenarios can be connected with conservation planning via adaptation pathways. An adaptation pathway is a decision strategy that entails a vision for the system of interest (here flatback turtles) exposed to anthropogenic risks, to be met through a sequence of manageable steps over time (Barnett et al. 2014). Change in conditions over time will present decision points where new actions are required (Wise et al. 2014). The adaptation pathways are not intended as multi-decade plans to be rigidly followed, rather they are foresighting tools to enable significant but uncertain future change to be considered and incorporated into existing planning in an adaptive manner (Wise et al. 2014). Adaptation pathways serve to identify additional actions that could be considered for including in the current or next planning cycle, in addition to existing management priorities, specifically to create options for future management based on foresight about future environmental change, the enabling conditions needed for managers and the temporal dependencies of those enabling conditions. Adaptation pathway analyses should be repeated regularly, updated by new insights regarding the future, to inform each cycle of management planning.

Further, the linking of threats to scenarios to adaptation pathways allows holistic 'future testing' of management approaches to navigate those threats (Fig. 1). Scenarios envisage underlying processes leading to change and describe how that change might plausibly materialise and be observed. Adaptation pathways formalise that thinking into a series of stages. The aim of the research presented here is to demonstrate how scenarios and adaptation pathways can support long-term conservation planning and practice. In the fol-

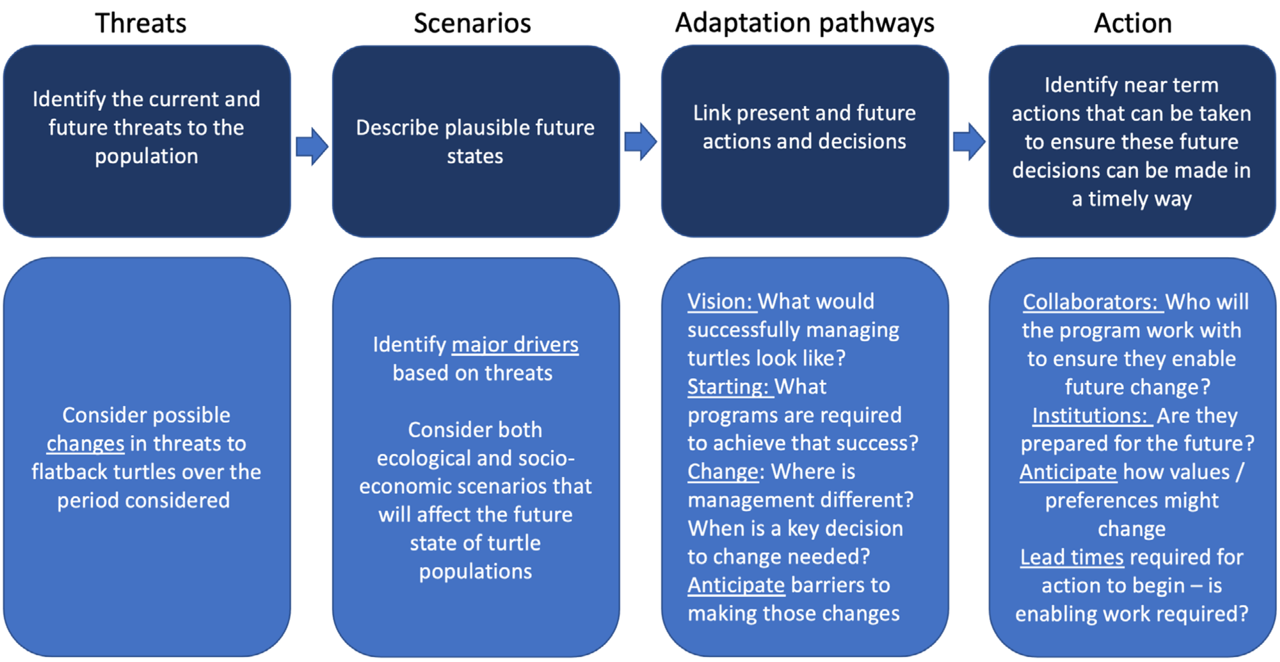


Fig. 1. Connections between identification of threats, development of long-term scenarios, development of long-term adaptation pathways, and how they lead to near-term actions for improving the long-term outcome for the system of interest, in this case flatback turtle

lowing sections, we describe the development of scenarios and then link these to adaptation pathways. Successful integration means that managers will have scope to address an uncertain future (Fig. 1). Each of the stages requires consideration of multiple aspects such as threats, drivers, vision, collaborators, and lead times (Fig. 1).

2. METHODS

The scenarios and pathways for flatback turtles in northwest Australia were developed based on repeated interactions (online and in-person workshops and email communication) between participants in a project over more than 4 yr of collaborative research. This approach is described here in general terms, and the results are intended to be illustrative rather than absolute.

2.1. Scenario development

Scenarios may be defined in terms of the drivers and combinations of future conditions that lead to alternative mutually exclusive future worlds (e.g. 2 × 2 quadrants, internally consistent, e.g. Costanza et al. 2011), or as narrative-based views that may not be mutually exclusive (Boschetti et al. 2020). Our scenarios are exploratory narratives focusing on possible flatback turtle population outcomes due to current and future threats. We developed 2 groups of future scenarios that described (A) a turtle population situation, or (B) a socio-economic situation. Each group included 4 different scenarios.

The threats that influence the population trajectory of the North West Shelf flatback stock were aggregated to 2 dimensions. The first dimension of climate change is due to increasing temperature and sea level rise. The second dimension of regional development encompasses light pollution, beach modification, marine debris, and introduced animals. Development pressures can also arise from infrastructure and population pressures arising from human migration in or out of the region. These 6 current and future threats have previously been prioritised following extensive review of this population (NWSFTCP 2014).

We focused on a time period which will coincide with the end of the 60 yr NWSFTCP (circa 2070), a timeframe over which some of these drivers could have transformational impacts on turtle populations and management. We developed plausible scenarios that were not mutually exclusive — more than one could occur concurrently. We explicitly considered 1 or more of the 6 threats to flatback turtles in drafting these scenarios.

We drafted 8 scenarios describing (A) the turtle population situation (Scenarios 1 to 4) or (B) a socio-economic situation (Scenarios 5 to 8): (1) a change in turtle spatial distribution, (2) an increase in the turtle population, (3) a decrease in the turtle population, (4) an external shock to the population in the form of an oil spill, (5) a change in public attitudes regarding turtle conservation, (6) intensified development in the region, (7) a decline in industrial activity in the region, and (8) an ecosystem management focus. Each scenario was less than 200 words for consistency, and then reviewed by all the authors, who include flatback turtle conservation managers and researchers, spanning a range of disciplines including biology, ecology, social science, and economics. We then considered these scenarios relative to the 2 dimensions (climate and development) to assess our coverage of plausible future conditions. Each scenario was structured to consider: (1) the observed system state at some location and time (here, the population status of flatback turtles within the Pilbara region in 2070); (2) the evidence that population factors (e.g. X, Y, Z) have changed; and (3) management actions that had been implemented prior to 2070, but not the effectiveness of these management actions.

2.2. Adaptation pathway development

Adaptation pathways can represent a sequence of decisions that can be anticipated, and that managers may need to make as the system changes over time, to achieve a successful conservation outcome in the long term. They are derived through a deliberative process that considers the evolution of the state of the system (Barnett et al. 2014, Wise et al. 2014) and the actions of managers and others necessary to enable the implementation of effective conservation action in a very different future environment. The key question driving the development of the pathways is what activities (actions) might be required sooner to create an enabling condition for future actions. This is particularly relevant given the long lifecycle of flatback turtles (Turner Tomaszewicz et al. 2022), and delayed observation in adult populations of anticipated but unseen impacts from environmental change and management interventions on hatchlings and juveniles (Richards et al. 2024). Adaptation pathways can be drafted using a range of software (i.e. drawing programs) or hand-drawn methods in drafting stages or where these programs are not available. The choice of drawing tool should consider that the adaptation pathways that are created can be easily shared and modified.

Each adaptation pathway was developed according to the following steps (see Fig. 2):

1. For each scenario we identified a vision of what a successful conservation outcome could look like in the face of the change. We identified the management actions that would be required, in the future, to achieve that desirable outcome.
2. We identified the current management and research activities relevant to the topic of the scenario.
3. We scoped the sequence of actions that bridge between the future desired outcome and the present. These include extending existing actions and starting new ones.
4. Key barriers to management associated with the sequence of events were then identified. These barriers included uncertainties about environmental change and turtle population responses, community acceptance of changes to management, and current policy that may inhibit future management options.
5. Sequences of decisions confronting managers that address the barriers identified were then mapped to connect the current management to the future management anticipated to achieve the desired outcome (state) for the scenario. The decisions were noted on an adaptation pathway diagram as the actions, and included management activities, monitoring, experiments, policy changes, and community engagement. Each decision was located along the timeline in the pathway noting what actions need to precede it, when it might need to be made, and the approximate duration of the action to achieve its intended outcomes. For example, experiments involving translocated hatchlings returning to their new natal breeding beaches need to last at least as long as it takes a hatchling to develop into a breeding female (~16 yr; Turner Tomaszewicz et al. 2022). In this iteration of the pathways, the timing for each action was largely relative (longer, shorter, before, after, coincident), rather than quantitative. This step can also include consideration of the other actors in the broader network of turtle stakeholders that might be involved in decision-making and action implementation (e.g. Ison et al. 2021).

Adaptation pathways were developed by sub-sets of the research team then validated as feasible, logical, and temporally sound by the rest of the project team. Inclusion of any adaptation pathways here does not represent acknowledgement of these as a currently desirable and intended course of action by the NWSFTCP; they are simply possible adaptation pathways and serve as illustrations of the methodology. The purpose of considering adaptation pathways that vary in desirability was to elicit and provide a rationale for near-term activities that could enable management options that might

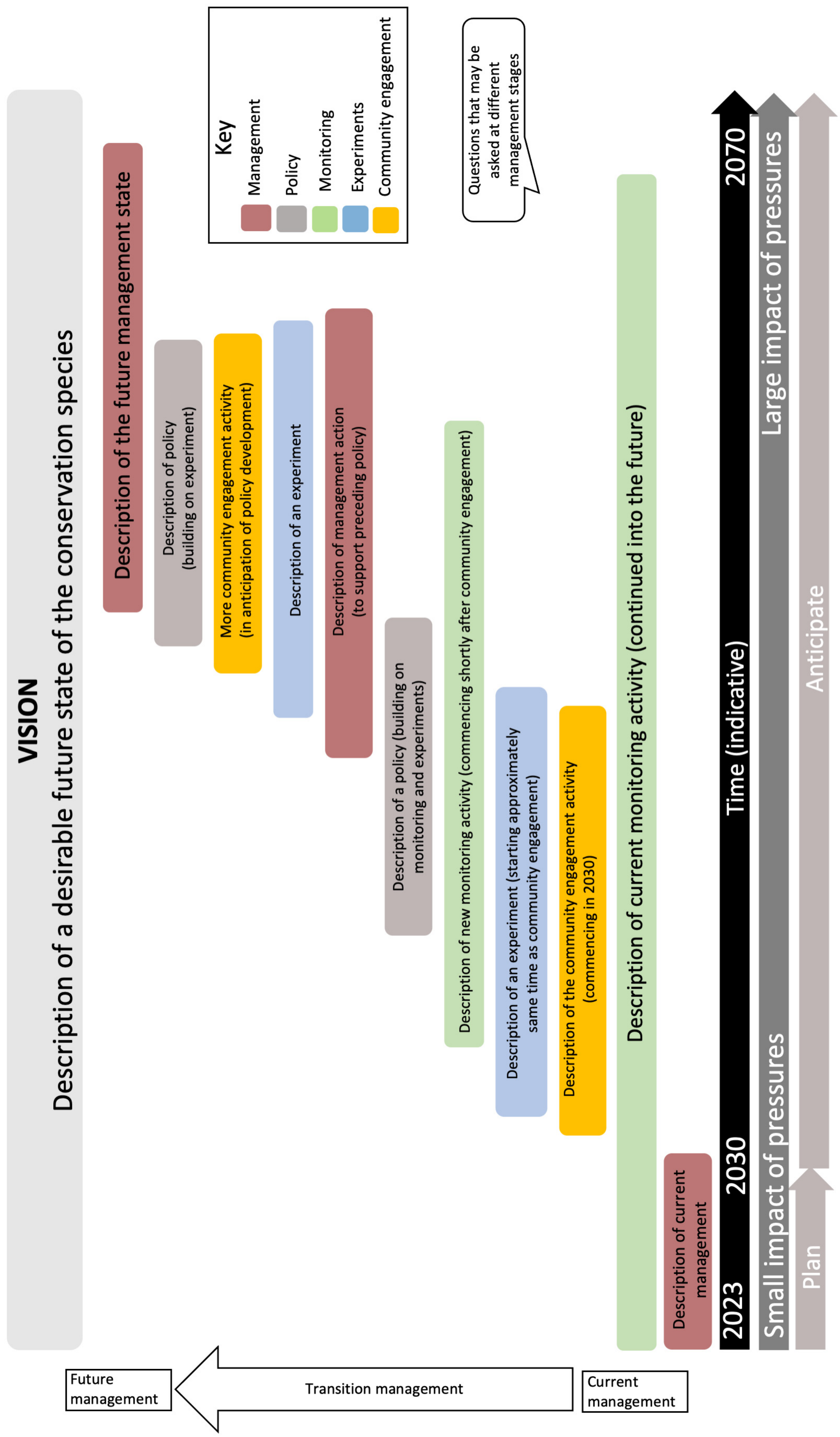


Fig. 2. Schematic of an adaptation pathway for a scenario, showing the vision, management stages, questions that should be addressed (speech bubble), and a series of actions of different types and the period over which they may be needed

be deemed necessary or desirable in the future. It is anticipated that some near-term actions, if implemented, could confirm the undesirability of some long-term options and may reveal alternative long-term options that should be considered in future adaptation pathways.

2.3. Exploration of future options for management of flatback turtles

In this research we sought to determine how the scenarios and adaptation pathways could help long-term planning, focus current efforts, and communicate to stakeholders why decisions are made. Once individual pathways were constructed, they were reviewed and compared, noting:

- Any near-term actions that were in common across multiple scenarios, which were identified as robust or low regret activities (with regard to the outcome desired). These actions could be incorporated into near-term plans with reduced likelihood that they may turn out to have been unnecessary.
- Future conditions or activities that might be critical, even if only required for one or some of the scenarios. These can then be assessed in greater detail to determine if responses need immediate implementation or can be delayed. Delaying actions allows for more knowledge about their future necessity to be accumulated without compromising the time required for the action or outcomes.
- The balance of management, research, policy, community and Traditional Owner engagement activities needed to satisfy the objectives of the flatback turtle conservation program.

3. RESULTS

3.1. Scenarios

Turtle conservation will be affected by the dynamics of turtle populations and societal factors, so we developed 2 groups each with 4 different future scenarios that described (A) a turtle population situation or (B) a socio-economic situation. Each of the scenarios considered different threats identified as relevant to the northwest flatback turtle stock by the year 2070 (Table 1).

Scenario 1. Distribution change. There has been a change in the spatial distribution of turtle nesting sites. A significant reduction in nesting has been observed at several rookeries that were core breeding units at the start of the NWSFTCP program back in the 2010s, and there has been a significant expansion of nesting at several new rookeries to the south of historical regions. Overall nesting success of the whole flatback population is broadly stable over time, but there has been a reduction in the suitability of traditional nesting beaches that has led to turtles failing to nest and seeking alternative nesting sites. This process occurred gradually over decades, with periods of low nesting success following years of significant beach loss due to erosion (multiple intense cyclones) leading to nesting turtles utilising other sites. There was also a gradual decline in hatching success at some major traditional sites, due to a variety of threats: warming, predation, loss/erosion of suitable habitat, and a suspected increase in hatchling predation once hatchlings enter the water. Coincidentally, through natural processes, there have been increases in nesting success at other sites, including those that tradi-

Table 1. Summary of scenario-threat links for flatback turtle *Natator depressus*. Each of the scenarios include reference to one or more threats as part of the scenario narrative, as indicated below (Y), but these do not imply cause and effect

Scenario	Driver group					
	Climate change threat			Development threat		
	Sea level rise	Increasing temperature	Introduced animals	Modification to beaches	Marine debris	Onshore and nearshore light
A. Turtle population state						
1. Distribution change	Y	Y	Y	Y		Y
2. Increasing population		Y				
3. Declining population	Y	Y		Y		Y
4. Shock event—oil spill		Y		Y		Y
B. Socio-economic state						
5. Change in public attitude				Y	Y	Y
6. Development intensifies				Y	Y	Y
7. Industrial activity declines			Y		Y	
8. Ecosystem management		Y	Y	Y		Y

tionally had very few nests. This decline and increase in nesting success, over generations, led to a natural change in the spatial distribution of the population as hatchlings return to their natal beach to nest.

Scenario 2. Increasing population. A steady increase in the female proportion of hatchlings due to warming of nests has resulted in a significant increase in the proportion of adult females. In the last 2 decades, the population has experienced a boom in the number of females nesting. This apparently good outcome has prompted a review of the requirement for the continuation of the NWSFTCP under the offset agreement. For the moment, observed increases in egg mortality and decreases in hatchling vigour as a result of warming have been compensated for by the increased total number of eggs laid. However, there are concerns that there will shortly be an abrupt and protracted decline in breeding success. Marine predators have adapted to the superabundance of hatchlings, a process that may accelerate any natural declines in nesting. The abundance of females has led to significant competition for nesting sites including disturbance of nests by other turtles. As the female hatchling ratio approaches 100% there could be insufficient recruitment of males to the adult population leading to a marked shortage of sires and possible deleterious genetic consequences from lack of diversity.

Scenario 3. Declining turtle population. Decreased numbers of nesting females have been observed at all core rookeries for this breeding stock of flatback turtles, including those rookeries at offshore islands. Monitoring efforts at 6 major rookeries showed that the overall population was relatively stable (or only slightly declining) for almost 40 yr; however, a decline has accelerated over the past decade. The evidence suggests that nesting success, which was also relatively stable, has also changed over the last decade. Rising sea levels are also leading to more frequent nest failure on some beaches, and attempts at coastal stabilisation (e.g. sea walls) have reduced natural sand nourishment processes and accelerated erosion elsewhere. Hatching per nest is lower, and surviving hatchlings are less vigorous. Hatchling survival in the first days of life is very poor based on short-term experiments with acoustic tags. Mark-recapture studies show that the females are generally surviving, but the average age of the breeding cohort is now quite old. Beach-washed individuals show evidence of malnutrition, and disease cannot be ruled out.

Scenario 4. Shock event to the population. The long-term impacts on flatback turtle nesting beaches from a large oil spill, caused by the running aground and breaking up of an oil tanker anchored off Dampier (NW Western Australia) during a category 6 cyclone, some 20 yr ago, are only just becoming apparent. The beaches from Dampier to Onslow seemed to have recovered after 5 yr of working around the clock to clean the beaches to depth of oil and dispersants. The light pollution and beach disturbance from removing and cleaning the contaminated sand has impacted both the nesting opportunities for female turtles and hatchling survival rate. Surveys conducted after beach rehabilitation show that hatching success rate is lower than before the spill as the sand structure has been changed, long-term monitoring shows female life expectancy is reduced by 30 yr, and studies have shown the microbes used to help clean up the spill have caused disease outbreaks in the turtle population during summer, when water is warmer because of climate change.

Scenario 5. Change in public attitudes. The NWSFTCP has been operating for over 50 yr. While previously the program enjoyed high levels of public support and participation, within the Pilbara region this support for turtles has declined. This change has been driven by (1) restrictions on the activities locals can undertake on local beaches and in the water during nesting season, (2) restrictions on local infrastructure development (and hence job creation) due to turtle protection, and (3) public concern about lack of funding for critical local infrastructure such as roads and hospitals, when millions of dollars are being spent on turtle conservation. These impacts have led to a loss of public interest in the conservation of flatback turtles in the region and a decrease in public support and participation in local turtle monitoring and conservation — meaning that many actions associated with the NWSFTCP can no longer be implemented effectively. Simultaneously, changes in public attitudes have led to an increase in non-compliance with local rules and regulations and adverse behaviours have intensified — such as 4-wheel driving on local beaches, interfering with nesting female turtles, and more local pollution and marine debris.

Scenario 6. Local development intensifies. The past 40 yr have seen significant expansion of existing industries due to ongoing demand for natural gas. At the same time an increased social push for a shift towards more renewable energy sources in Australia has seen the diversification of the local energy industry which now also includes significant solar farms (on land), wind farms (offshore), and a hydrogen manufacturing and export plant. These expansions have created thousands of new jobs in the region; however, the social push towards more renewable types of energy has also led to loss of public support for fly-in fly-out (FIFO) jobs, given high carbon budgets associated with flying. The combination of new jobs from new industries and a reduction in FIFO operators has caused a 30% increase in permanent residents living in coastal towns. Thus, not only has there been an expansion in industrial development, but significant developments are also underway to increase housing capacity in the area, expanding local schools to meet growing enrolments, and so on. These expansions in local infrastructure have reshaped the local environment, resulting in the intensification of local development pressures on turtle nesting sites associated with human population growth such as increased artificial light, pollution, and beach use and modification.

Scenario 7. Industrial activity declines. The oil and gas industry has packed up and left town, but the infrastructure is still sitting idle. Over the past 50 yr, the industry has been winding down in line with international climate change obligations. All offshore infrastructures have been cleaned up in line with regulations, but the companies have not been required to undertake the same level of clean-up onshore. The government has not been able to attract (large) new industry to coastal towns, and repurposing of infrastructure has thus far failed. Consequently, many residents have moved away to find employment, and industrial activity in the region is in decline. Aside from people working in tourism, those who remain are largely reliant on public benefits. Services like schools and medical facilities, but also local environmental NGOs and volunteer organisations, have slowly closed due to declining population numbers. This has led to people becoming careless about disposal of their waste (which is no longer collected regularly). Plastics are entering the environment and impacting turtles. Moreover, increasing dog and feral animal disturbance of nesting females and nests has occurred.

Scenario 8. Ecosystem management. Flatback turtle populations have increased significantly, and the species has been removed from Australia's threatened species list. While this is a good outcome, it also means the species has lost the status that confers its high level of legislative protection. The focus of the NWSFTCP therefore shifts towards ecosystem management and multi-species conservation, control of non-native species, and the protection of critical turtle habitats to maintain this trend. At the same time the expansion of the renewable energy industry in Australia, supported by the public, has seen a rapid increase in the number of remote sites, including protected areas, being leased for industrial exploitation. Several of those remote sites are critical turtle habitats, and continuing spatial expansion of this new industry is resulting in threats to turtle breeding in previously untouched areas. The change of conservation status and shift to whole ecosystem management means conservation actions need to be implemented through collaborative agreements, voluntary actions, positive incentives and other innovative mechanisms, rather than through regulation and legislatively backed controls, such as offsets.

3.2. Overview of scenarios

These scenarios illustrate the way in which the dominant threats in the region may play out over the next 50 yr, as indicated by placement of the scenarios relative to development and climate change (Fig. 3, Table 1). The spread of scenarios indicates that there was contrast in considering possible futures. These scenarios also include some threats that are not currently considered in flatback turtle management.

3.3. Adaptation pathways

Adaptation pathways for each of the 8 scenarios were generated that linked a vision with the current conditions. In each adaptation pathway, the man-

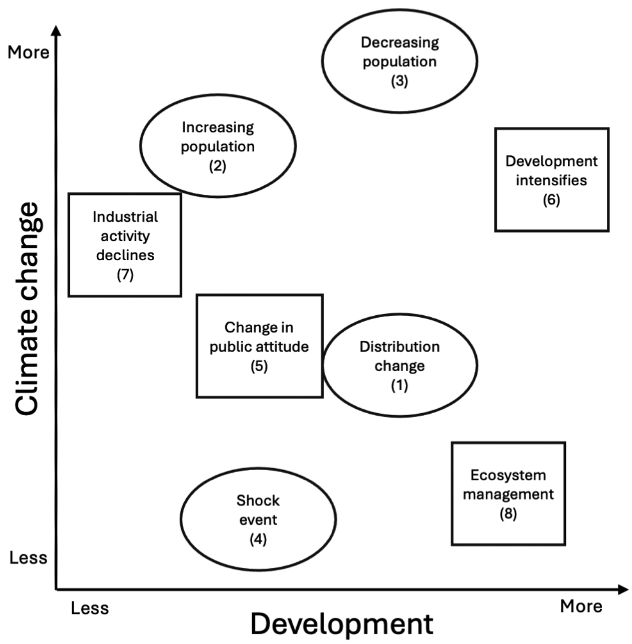


Fig. 3. The main threats to flatback turtle populations are linked to the extent of development and climate change. Each of the population state (1 to 4, ovals) and socio-economic (5 to 8, squares) scenarios emphasises a different combination of possible levels of future development and environmental change

agement, monitoring, experiments, policy changes, and community engagement actions were described. Key management questions were identified for some aspects. Draft pathways were discussed between project members and timing and sequencing considered. These revised pathways are presented here, but in use they will be updated and modified over time.

Adaptation pathway for Scenario 1. Distribution change. The vision for this scenario is that healthy flatback turtle populations are breeding in the region, which may require protecting new locations and reducing threats in these currently non-core regions (Fig. 4). The adaptation pathway may involve analysis of current nesting success patterns to identify rookeries impacted by warming temperatures and future site selection studies, followed by translocation experiments if natural movements are too slow. Monitoring to assess hatching success will be a first step, and then it will take many years to determine if recruitment to the natal beaches is occurring. Some mass translocations may need to occur before the results from these experiments are known, which will likely require regulatory approval and strong community and Traditional Owner support. Engagement efforts may be needed to build this support, which may take several years. At the same time, efforts to reduce the impacts of threats at existing colonies (lower part of Fig. 4) will be important to protect source populations.

Adaptation pathway for Scenario 2. Increasing population. An increasing population may seem at first to indicate success; however, the scenario suggests that the increase is due to feminisation, and is thus a short-term gain only. The vision for this pathway is to have long-term persistence of flatback turtles in the WA region, including at beaches further south than currently used (Fig. 5). Research and monitoring to assess the female ratio in hatchlings over time will provide a 16 yr advance warning that females will increase relative to males. Additional insight can be obtained by monitoring the operational sex ratio of males and females on the breeding grounds (Staines et al. 2022), although this signal may lag hatchling signals. To maintain balanced sex ratios, interventions to cool nests must be considered, as has been tested for green turtle nests in eastern Australia (Smith et al. 2021, Young et al. 2023). These interventions will require experiments to determine the best approaches, which may differ in social acceptability. As with the other pathways, engagement efforts to engage and build community and policy support will be needed, all of which require time and resources before efforts can proceed at large scales.

Adaptation pathway for Scenario 3. Declining turtle population. The adaptation pathway for Scenario 3 is less certain, due to the intentional ambiguity in the scenario, which reflects the likely situation that would be observed based on monitoring to date. The cause of the decline is unknown in the scenario, and so pathways that cover quality of foraging grounds (Fig. 6A), beach quality (Fig. 6B), and hatchling survival (Fig. 6C) will be developed. In all 3, monitoring is needed to inform the actions that could be taken. At some point in the future, the steps implemented as part of all 3 adaption pathways will point to 1 (or more) cause(s), and actions in that pathway can be emphasised and activities in the other pathways reduced or discontinued.

Adaptation pathway for Scenario 4. Shock event leading to population impact—oil spill. The adaptation pathway (Fig. 7) shows the actions that may be needed to develop an effective capacity to manage large oil spills that arrive at nesting beaches. Current responses are informed by experiences in Australia and elsewhere, with management response based on oil spill guidebooks and policies (e.g. AMSA 2017). Expertise from other regions can also be sourced now and in the future for some aspects, such as sand cleaning methods and hydrocarbon dispersion. The pathway example shows that to prepare for an intervention such as large-scale off-beach egg incubation, community engagement and preliminary experiments may be needed. These can then inform a new approval process and policy. Similarly, sand cleaning methods to avoid the outcomes described in the scenario must be tested ahead of time and can lead to new best practice guidelines. Finally, to clean up hydrocarbon, methods that do not impact on turtles may be investigated; this will take some time before results are known. Baseline turtle population monitoring (Fig. 7) will need to continue, as will oil spill monitoring and surveillance. While shock events such as oil spills might occur at any time, recognising the options for researching and preparing for managing shocks may still be useful. If shocks are increasing in frequency, then preparation and response will improve over time; however, there may not be a trade-off between when an event might occur and the preparatory investment — should it be made sooner rather than later (which is a feature of many adaptation pathways).

Adaptation pathway for Scenario 5. Change in public support for turtles. The adaptation pathway for Scenario 5 (Fig. 8) shows the actions required to successfully manage turtles towards the year 2070 without strong public support. That future means that current activities that receive public support may

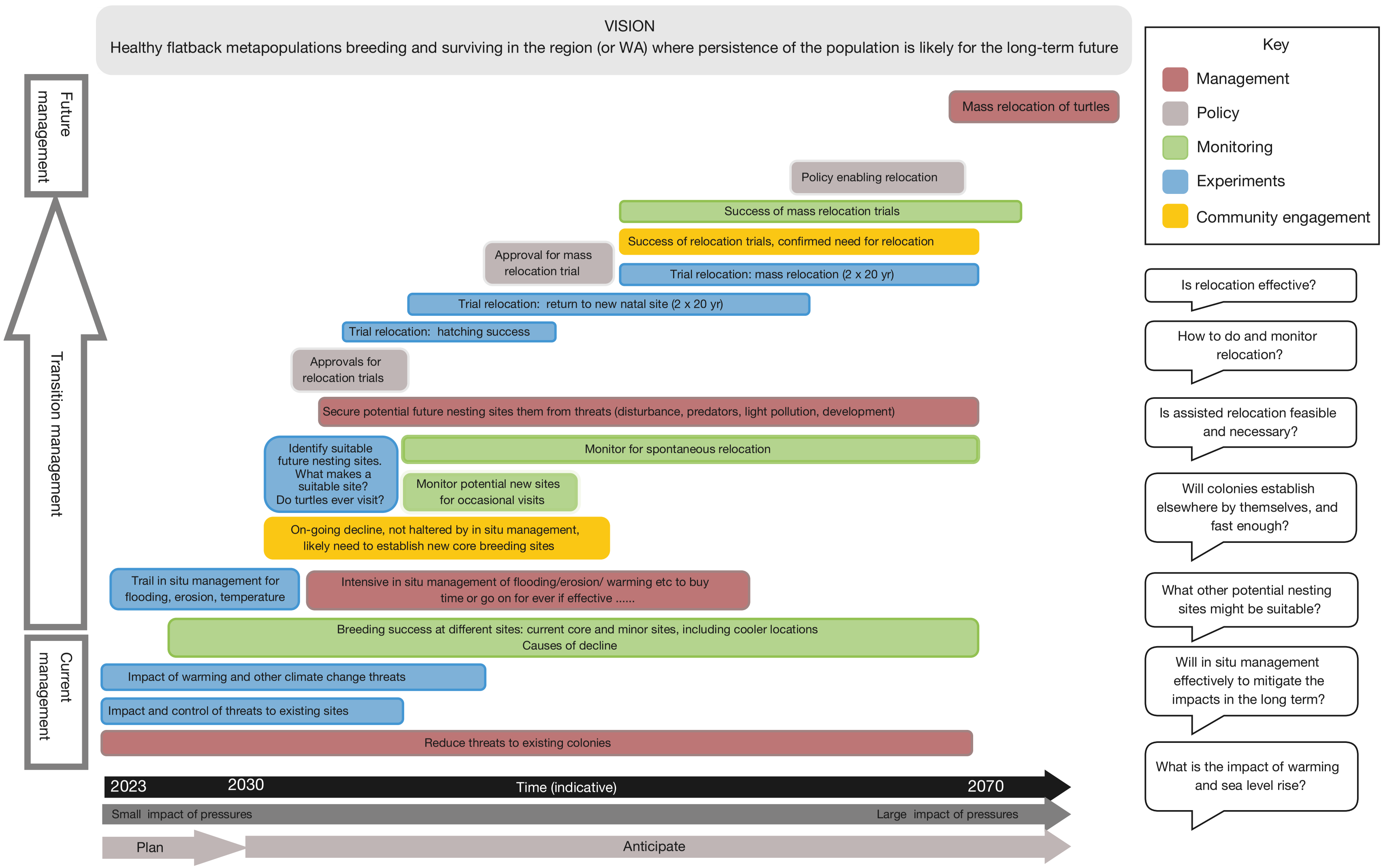


Fig. 4. Adaptation pathway for Scenario 1: Distribution change in flatback turtle nesting sites. The desired future state is indicated at the top of the figure, while the current management state is on the lower left. Key management questions are in the speech bubbles on the right, and the actions required to achieve the future state are arrayed from lower left to upper right. Different classes of actions are indicated by colours as shown in the key

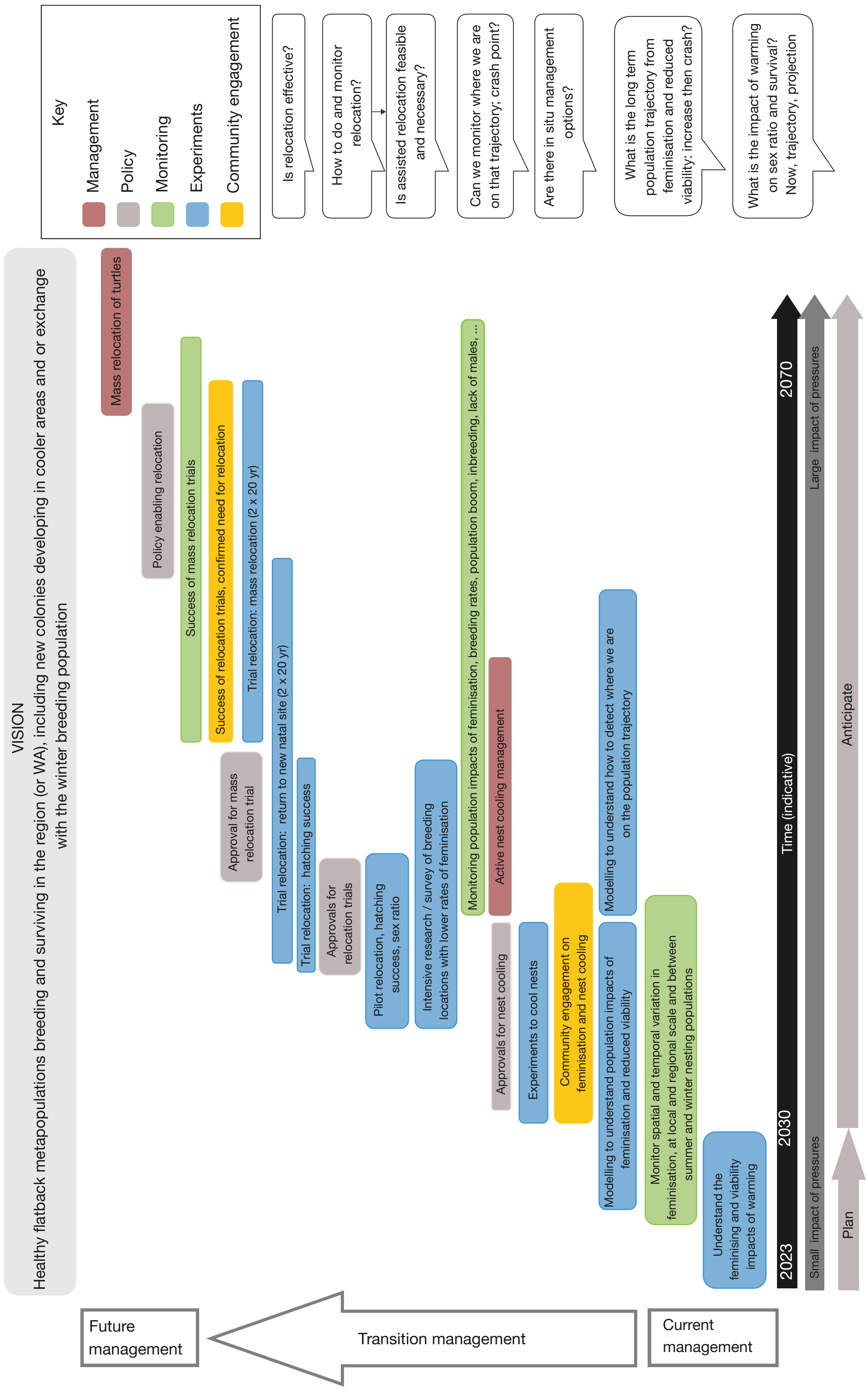


Fig. 5. Adaptation pathway for Scenario 2: Increasing flatback turtle population. Layout as described in Fig. 4

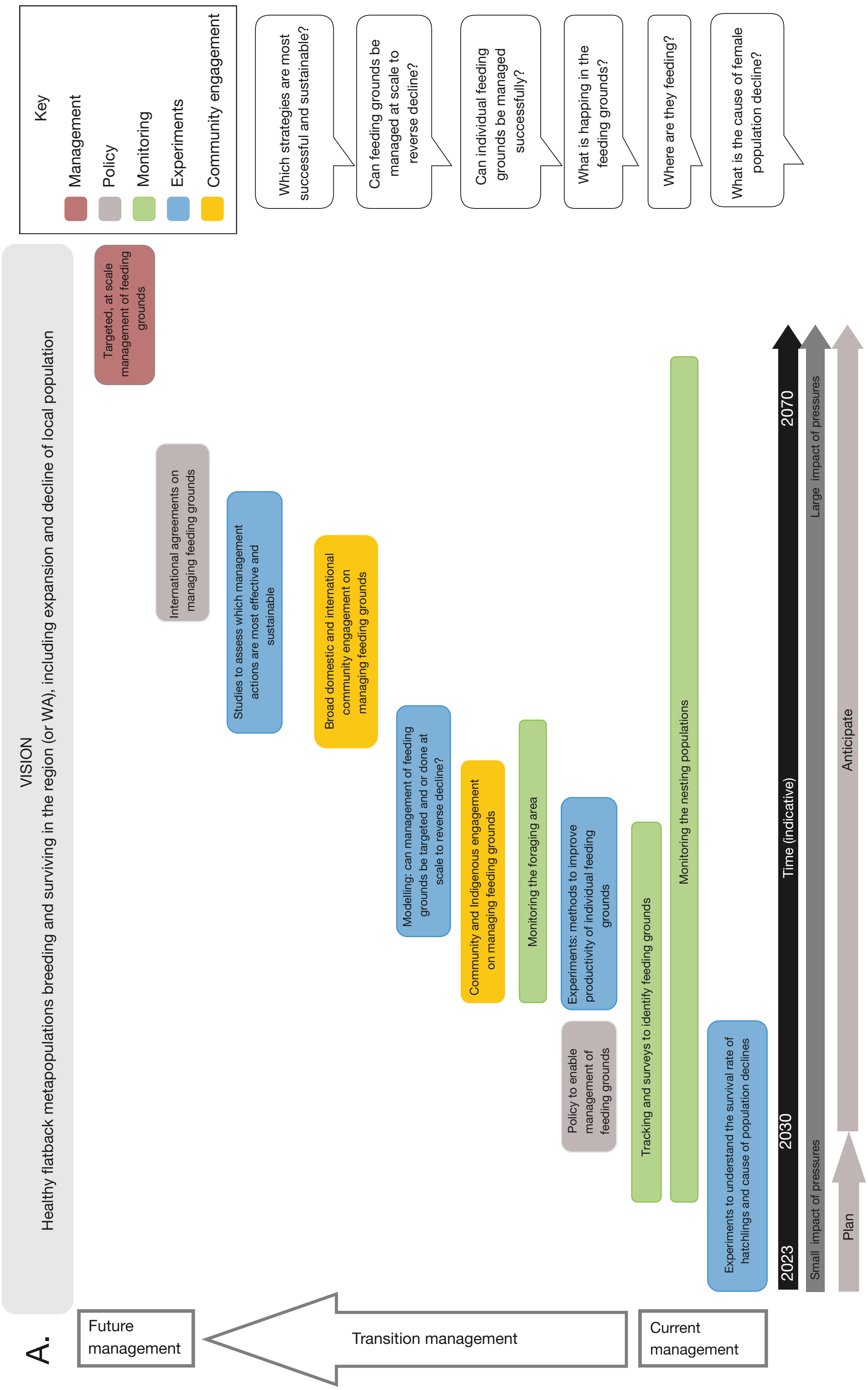


Fig. 6. Adaptation pathways for Scenario 3: Flatback turtle declines due to (A) issues on feeding grounds, (B) loss of beach habitat, and (C) hatchling survival. Layout as described in Fig. 4

Fig. 6 continued on next pages

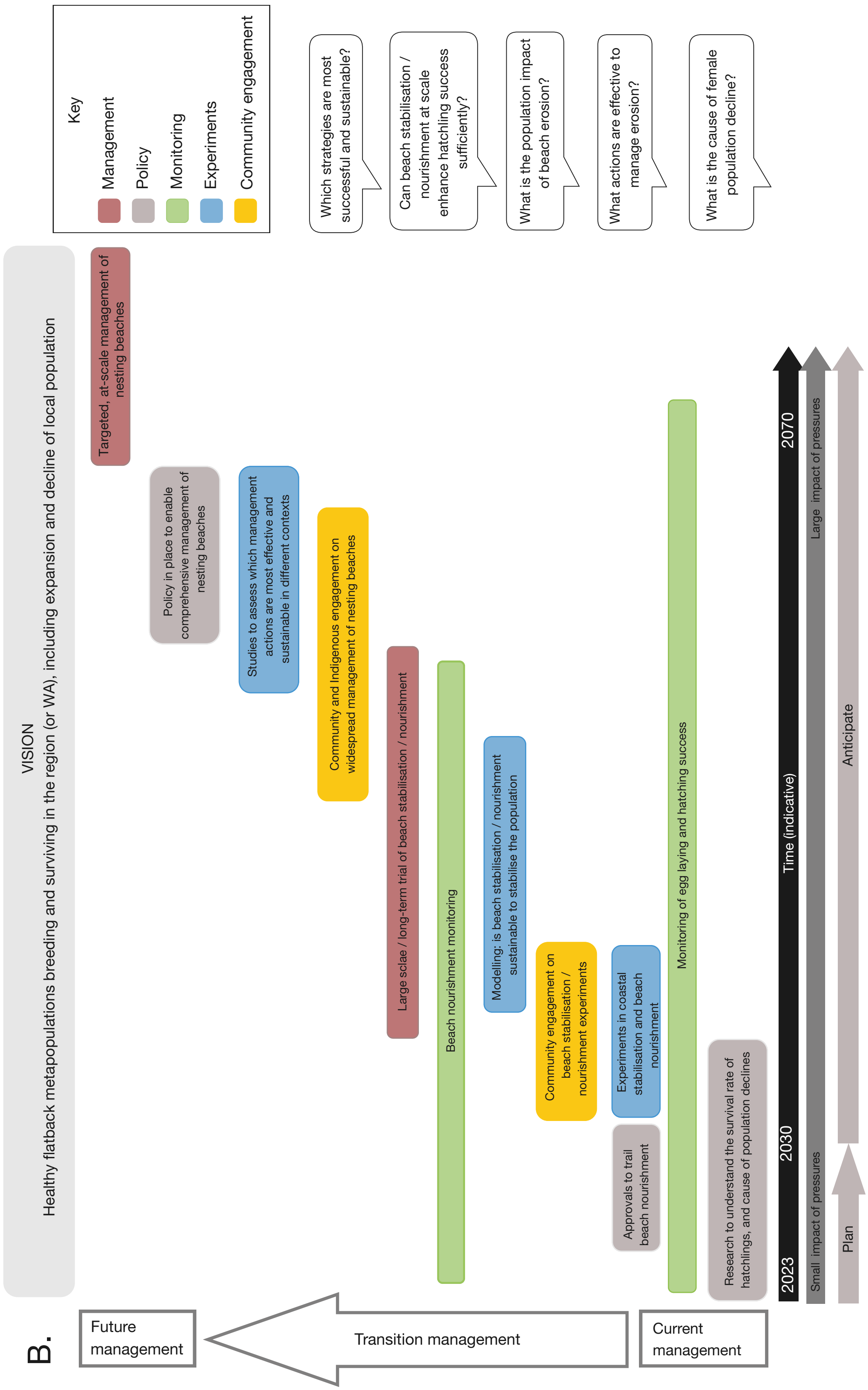
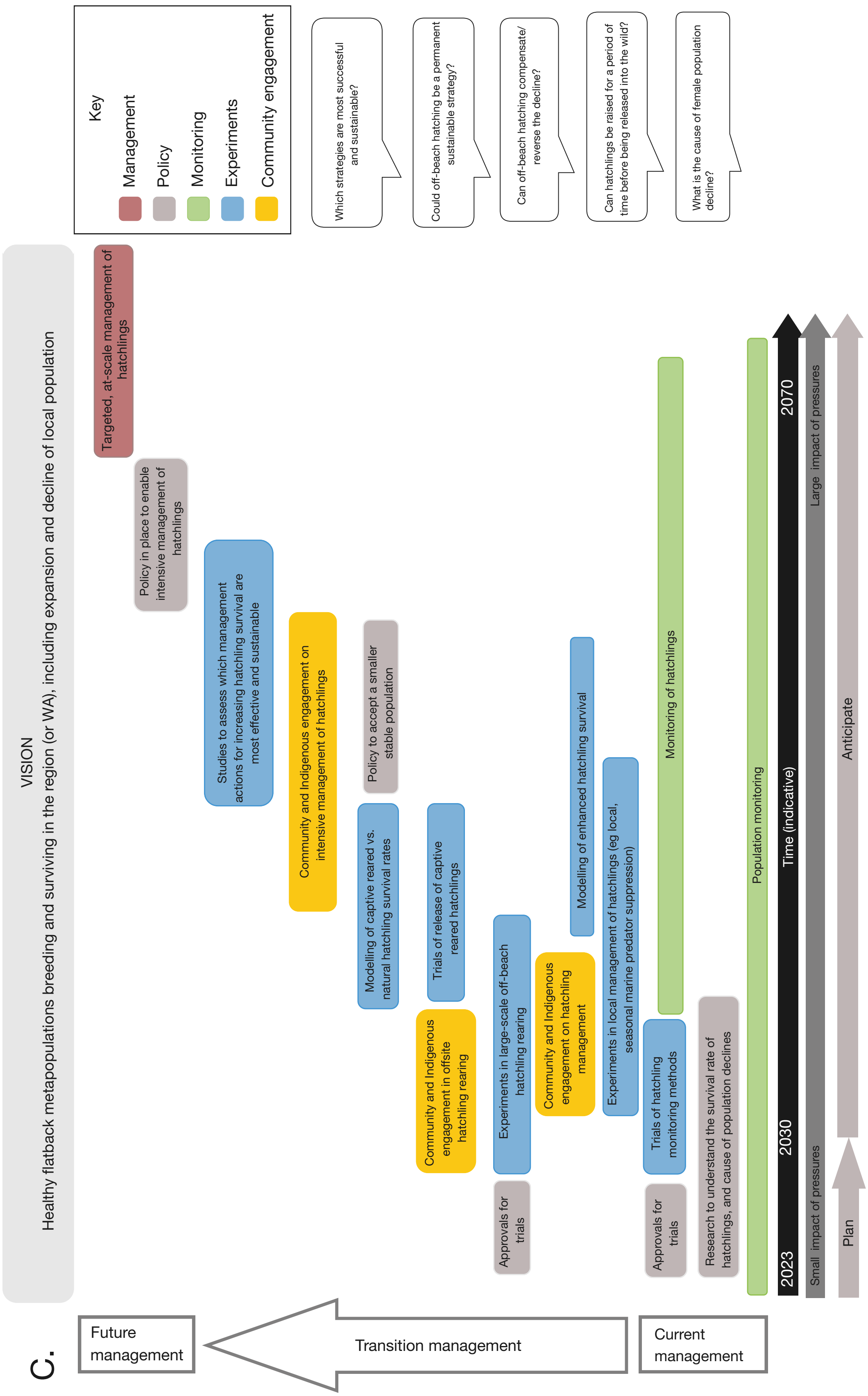


Fig. 6. (continued)



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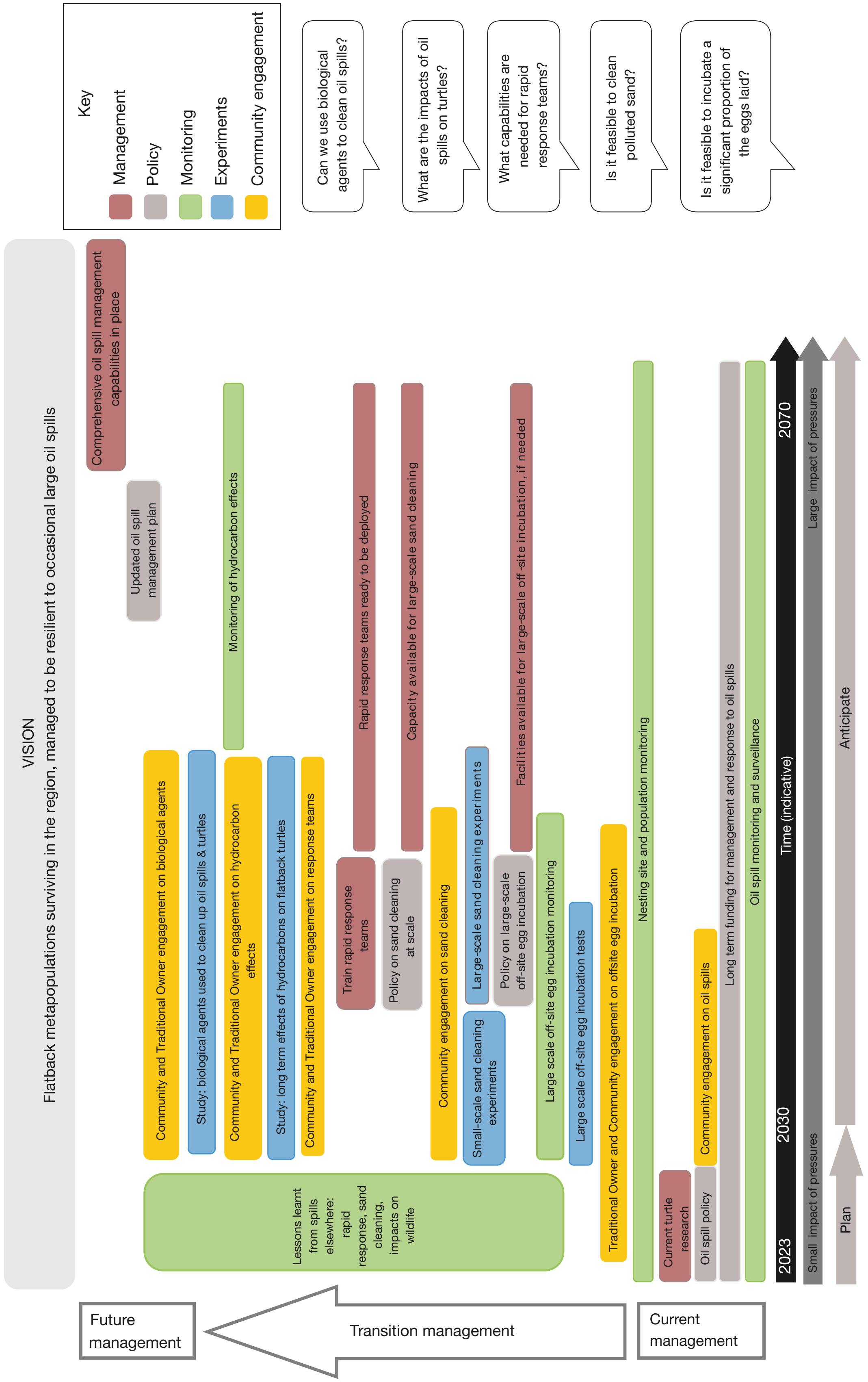

Fig. 7. Adaptation pathway for Scenario 4: Shock event leading to population impact—oil spill. Layout as described in Fig. 4

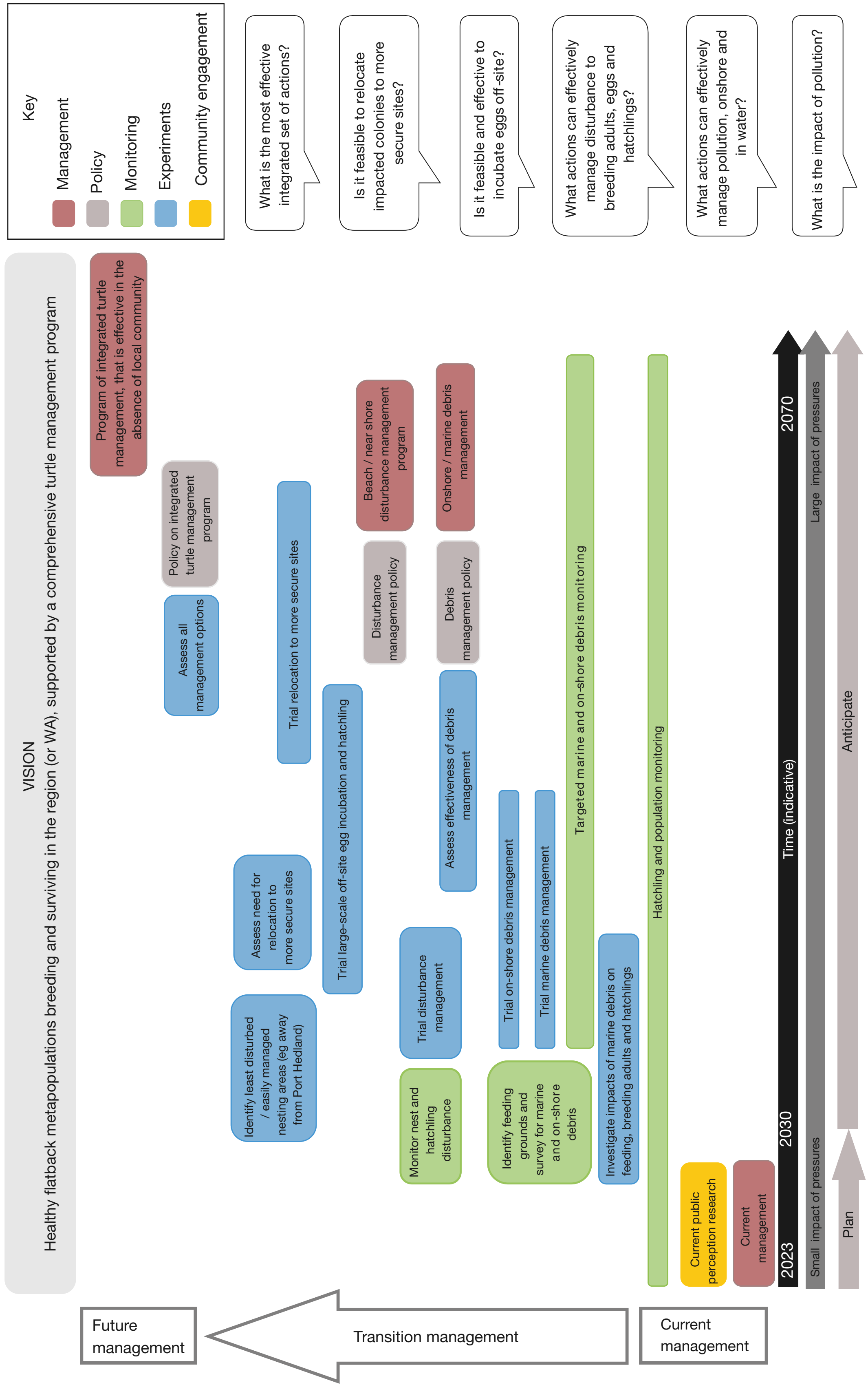

Fig. 8. Adaptation pathway for Scenario 5: Change in public support for turtles. Layout as described in Fig. 4

need to be addressed by a turtle management program. For example, support for protection of rookeries, waste disposal, and volunteering to monitor hatchlings may all decrease. As a result, turtle managers may need to directly address remote area waste management, on land and in the sea. Working back towards the present day, this might involve strategies such as deploying rubbish booms or investing in beach clean-ups. Carrying out this action effectively will require surveys of litter (e.g. Lavers et al. 2019) and trials of alternative litter management actions, both on shore and in the water (Willis et al. 2022). New clean-up technologies, such as offshore rubbish booms, may take a decade or more to be developed. Likewise, to ensure rookeries are not disturbed, increased ranger patrols will be needed, and more intensive management will be implemented. An alternative to both these actions is to redirect turtle conservation efforts to areas remote from human activity. This will require suitable beaches to be identified and surveyed, and approvals granted in the case that more active intervention, such as translocation is required.

Adaptation pathway for Scenario 6. Local development intensifies. The adaptation pathway for an increase in local development must ensure that turtles can persist in an environment with increased infrastructure (Fig. 9). Based on the scenario, increases in solar power, offshore wind, and traditional port development will all crowd the waters used by flatback turtles. Management must address questions regarding the most effective ways to ensure compatibility with increased shipping, wind farms, and waste management. It will be important to build community support for turtles and their environment and thus engagement efforts must be a priority. Studies showcasing the diversity and uniqueness of the regional flora and fauna and discovering the impact of development may help build support for greater protection and guide the design of effective integrated management responses. Experiments in waste, infrastructure, and biodiversity management can be undertaken to guide turtle-friendly development policies. Monitoring to detect any negative trends must be implemented early and must expand from the current focus on nesting beaches and hatchling rates to include measures of turtle performance and signs of possible pollution or poisoning. Given the additional development in turtle areas, funding levels may increase and support all these actions.

Adaptation pathway for Scenario 7. Industrial activity declines. While industrial activity declines in the areas where flatback turtle nest might seem to be advantageous, additional planning is required for success in 2070 under Scenario 7. The adaptation pathway (Fig. 10) shows that success might be achieved if management plans are in place to reduce the impact of abandoned infrastructure and human rubbish. These plans will need to be funded, which might involve lobbying for clean-up levies, decommissioning approvals, and funding for site rehabilitation. Decommissioning and waste management experts will need to be informed about the importance of turtle habitat when they provide advice to industry and government. Full or partial abandonment of some areas by people might result in increased populations of non-native pest animal and plant species (Quintas-Soriano et al. 2022), which will also require expert attention and new plans for nesting beach management. Community engagement will be an important action to build support for a managed decline in infrastructure, rather than abandonment, and remaining communities might represent a source of new volunteers interested in turtle management and protection. Traditional Owners already play an important role in caring for Country, and this custodianship role can be further empowered in the region.

Adaptation pathway for Scenario 8. Ecosystem management. Increases in turtle populations, and removal of their threatened status, will stimulate significant changes in the focus of marine conservation in the region (Fig. 11). The current focus on flatback turtle populations with its legislative backing, including a large offset, is replaced by a focus on whole-ecosystem management, positively incentivised conservation partnerships with industry (as opposed to regulatory mandated ones) and the need to raise resources from public sources. Each of these actions will require new knowledge and skills, developed through learning from elsewhere, and experimenting in the specific context. They will also require creating different types of relationships with industry and donors, based on how they value ecosystems in the region as a whole and flatback turtles in particular. Fostering this understanding and value for nature in the region, and flatback turtles in particular, will become an even more important part of the conservation strategy.

4. DISCUSSION

It is possible to be surprised, and at the same time be prepared (Grabo 2002).

Here, we have illustrated how scenarios can be developed for a future represented by 2 major dimensions of change (climate and development), following methods common to foresighting efforts (e.g. Boschetti

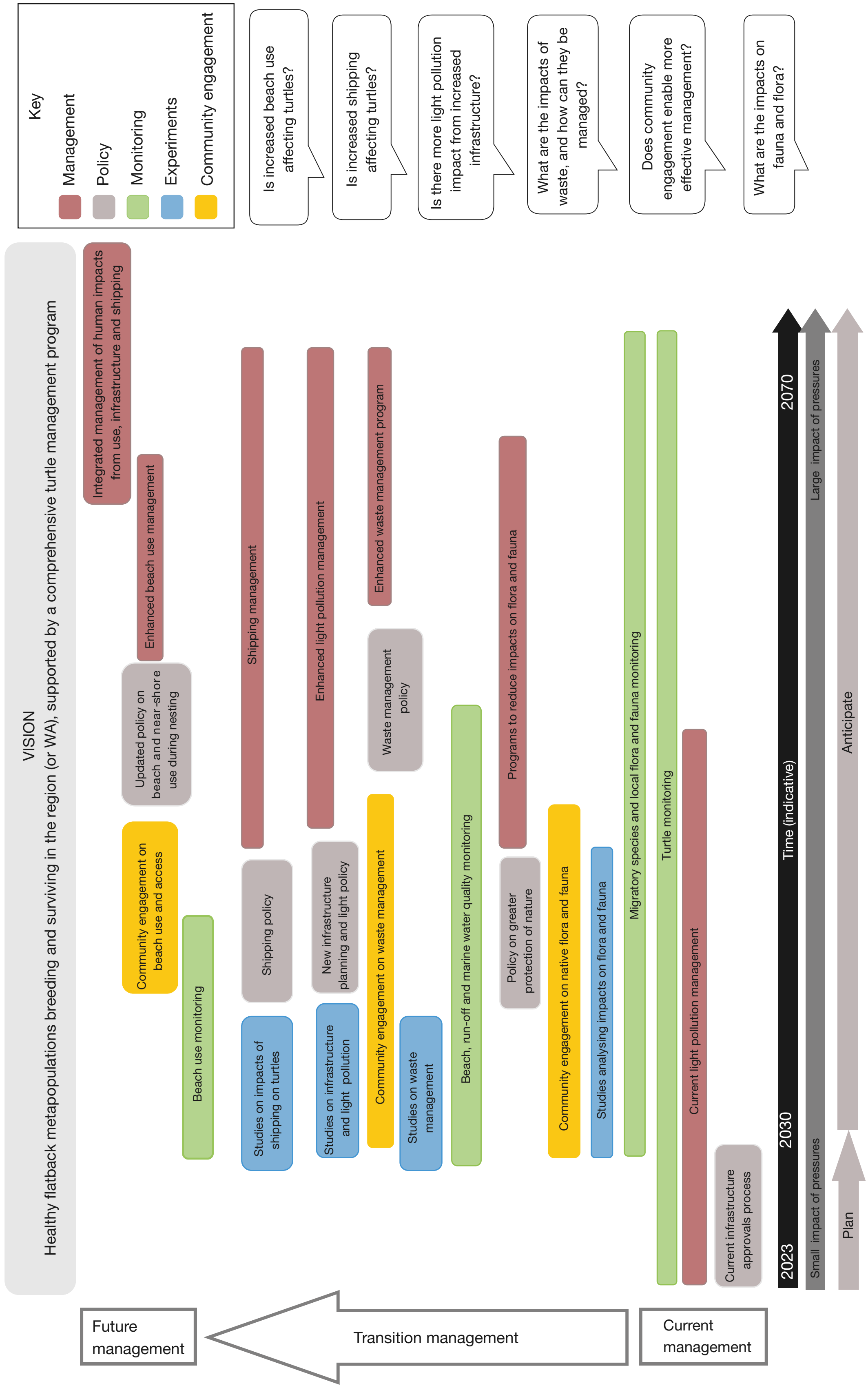

Fig. 9. Adaptation pathway for Scenario 6: Local development intensifies. Layout as described in Fig. 4

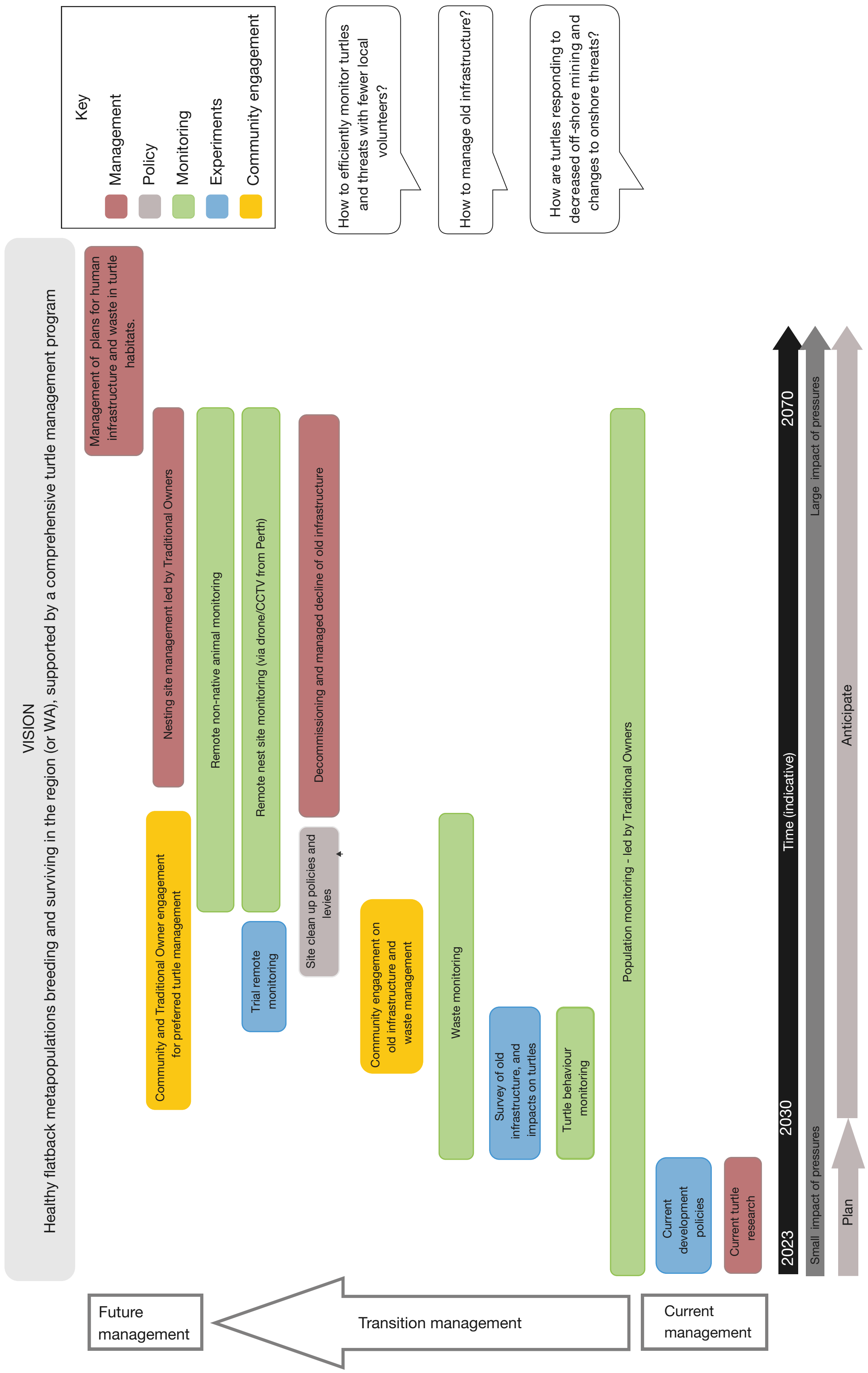

Fig. 10. Adaptation pathway for Scenario 7: Industrial activity declines. Layout as described in Fig. 4

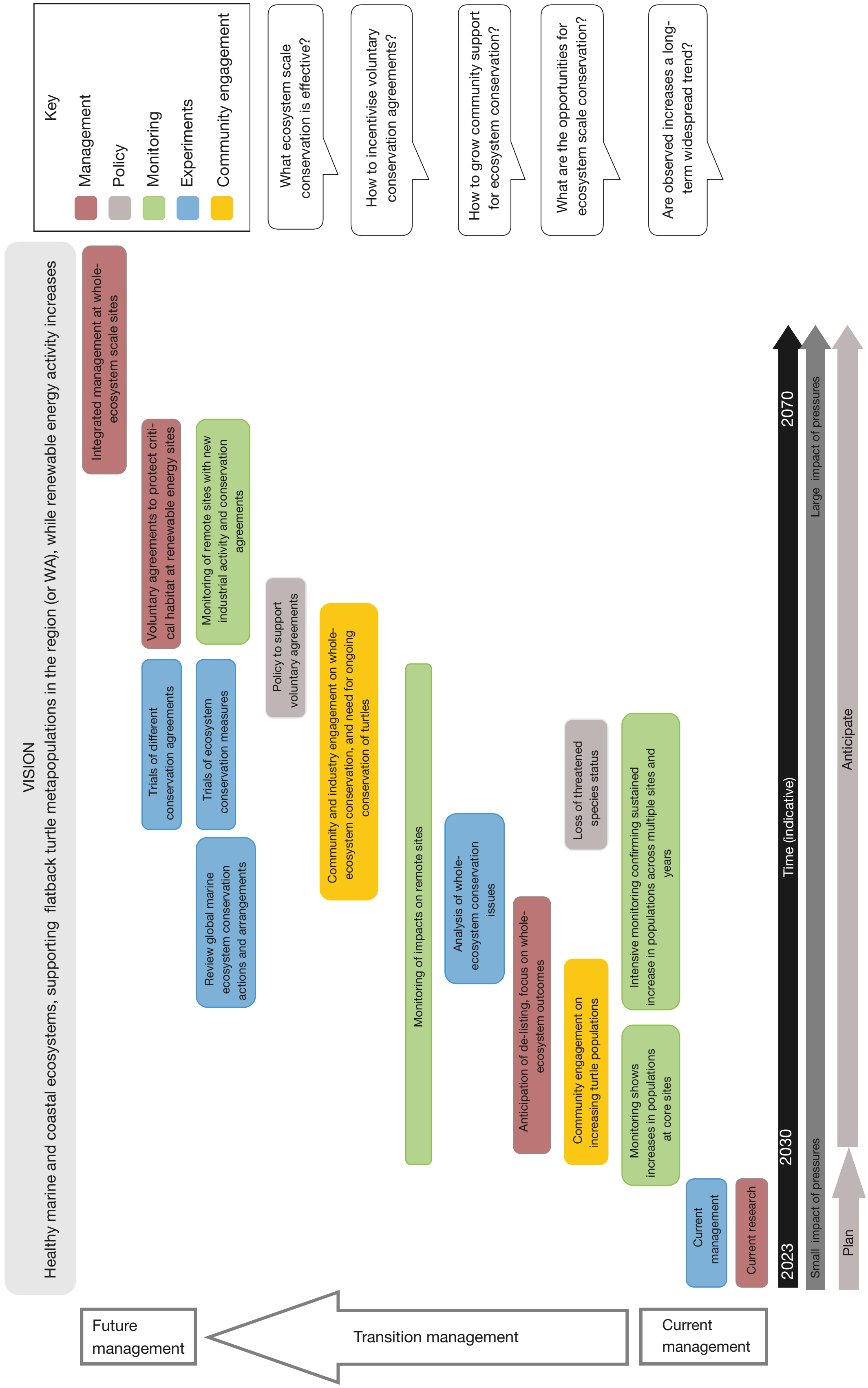

Fig. 11. Adaptation pathway for Scenario 8: Ecosystem management. Layout as described in Fig. 4

et al. 2020). We created example adaptation pathways to arrive at a long-term goal that represents success for flatback turtle conservation under each of the 8 scenarios. These adaptation pathways each contain several education, policy, monitoring, management, and experimental actions, some of which were found across multiple pathways, while others were limited to particular adaptation pathways. These methods can also allow multiple threats and synergies in management actions to be considered (Fuentes et al. 2023). Additional barriers may also occur in these scenarios, such as changes in funding because of changes in industrial development (e.g. Scenarios 6 and 7) or levels of community support (Scenario 5).

Common aspects to all the adaptation pathways were the extended time frame that was needed to build community and policy support for actions to arrive at the 2070 vision. Experiments all had a long lead time, particularly those focused on nests, eggs, and hatchlings, as adult turtles do not return to nest until ~16 yr later. Multiple pathways may exist (e.g. Scenario 3), and some actions will lead to positive outcomes for multiple scenarios. In all these scenarios and adaptation pathways, development of capacity for faster detection of population impacts and trends will increase the time available for implementing actions. While increased monitoring may lead to more accurate projections from the limited observable population (e.g. nest success parameters), additional measurements of other population life stages (e.g. parameters on juvenile survival, adult condition at sea) may provide additional warning of impacts.

Current monitoring also focuses on high density flatback populations, where animals can be easily and efficiently sampled. The adaptation pathways identified that while sampling is expensive, it will be important to build knowledge about the population and breeding trends in smaller outlying sites, as they may become more important in a changing climate (Gammon et al. 2023, 2024) and with alternative development scenarios (Fuentes et al. 2020). Trends in turtle population may mask negative outcomes, and so an ability to differentiate population increase due to feminisation rather than overall population growth is important to develop (Richards et al. 2024). Similarly, methods to determine when population decrease is due to climate, or to other factors, must be established to select the best action for long-term persistence. Survey techniques to determine the number and ratio of adult males in the population (Staines et al. 2022) can be used to determine if growth in the nesting population is due to greater hatchling survival of both sexes or if it is climate-induced feminisation. Use of 'second order' population parameters (e.g. chemical loads in adults, or baseline body conditions, e.g. Young et al. 2024) may help distinguish between different threats and causes of mortality. Models can also be used to identify fingerprints of different threats (Richards et al. 2024). Community support will be needed in all these adaptation pathways (e.g. Ison et al. 2021), and education will be needed to build support for interventions in turtle life history (Hobday et al. 2024) and for reducing the threats to turtles.

Some actions were specific to just 1 or 2 scenarios, but these actions could be critical to the success of turtles if these scenarios emerge by 2070. For example, translocation to alternative breeding beaches has many uncertainties to be explored before this might be a feasible and reliable option at scale. Prior to large-scale translocation of eggs in nests (e.g. Scenarios 1 and 2), suitable locations, timing, frequency, and complementary actions (e.g. reduction of nest predators) must be tested. Traditional Owners will need to be involved in any discussions regarding translocation away or to Country, as increasingly occurs for terrestrial translocations elsewhere in Australia (e.g. Moro et al. 2024). Actions for effective mitigation of a shock event (Scenario 4) such as an oil spill, which requires very rapid implementation when a spill occurs, need to be initiated many years ahead of an event, as it could take many years to build the knowledge, capacity, and policy to cope with a shock. Several adaptation pathways include actions that could allow for mass off-beach egg incubation. While this is a common practice in conservation around the world, the effectiveness for many locations is unknown, and very large numbers would need to be incubated given low post-release survival (e.g. Heppell et al. 1996). The long time between hatchling release and adult breeding means these experiments need sustained monitoring programs and may require new genetic methods (e.g. Patterson et al. 2022) to match returning individuals with hatchlings.

While we posit that these scenarios and adaptation pathways are indicative of the range of futures faced by flatback turtles, other futures and barriers are also possible. Given that some of these cannot be predicted, identification of actions that can occur regardless of the future is particularly useful for turtle managers. As there will be novel circumstances that will challenge the status quo, there must be an increased focus on community engagement to prepare supporters and critics for unforeseen changes, to encourage greater efforts in citizen science and surveillance, and to gauge and build support for different interventions (van Putten et al. 2023). Public support will be important if policy changes are needed, for example, to accommodate spatial changes in nesting populations and permit different types of interventions. Public understanding about the uncertain future is also needed if more speculative experiments are required to prepare for the mitigation of future threats (e.g. Lockie et al. 2024). Finally, additional research on population impacts of future threats and design of broad monitoring and surveillance programs that can detect differing threat impacts are needed.

These efforts at scenario development and adaptation pathways provide managers of flatback turtle with a long-term view of the actions and lead times for these actions that may be needed to maximise the long-term likelihood of persistent populations. In some of these futures, self-sustaining, resilient, adaptive populations that can adapt to environmental change with minimal management intervention are possible. In others, healthy flatback metapopulations breeding and surviving in the region will only be possible with considerable intervention, and areas outside the current range (e.g. cooler beaches to the south, e.g. Gammon et al. 2024) may become important in the future. Thus, engaged local and remote communities and Traditional Owners must value flatback turtles, be supportive of management actions that have been tested in models and pilot experiments, be willing to accommodate trade-offs, participate as volunteers, and report unusual observations. These communities should also be engaged in multiple aspects of turtle management and have access to livelihood options associated with turtles, such as tourism businesses. Traditional Owners have a long and rich history involving turtles, and these connections must be recognised and enhanced. Research programs like the NWSFTCP have supported increased Traditional Owner involvement and leadership in monitoring and research, and have sought to build capacity to engage in additional employment and business opportunities related to turtle management and tourism.

Overall, the outcomes from using long-term planning tools as illustrated here prepare turtle researchers, managers and policy makers, and communities that value turtles for responding to the emerging and future threats to the persistence of this species. These tools may encourage investment in the capacity to detect undesirable trajectories, and in actions that can be used to intervene rapidly and effectively. As the future, and the emerging threats, can change with time, these tools and the products should be routinely examined and updated, as part of a long-term strategy to guide research and management plans.

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