Coproduction mechanisms to weave Indigenous knowledge, artificial intelligence, and technical data to enable Indigenous-led adaptive decision making: lessons from Australia’s joint managed Kakadu National Park

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ABSTRACT. Most of the planet’s vital ecosystems are managed on lands owned by Indigenous peoples. Indigenous people face many challenges in managing these lands, including rapidly growing threats causing species extinctions and ecosystem losses. In response, many Indigenous groups are looking for ethical ways to use digital technology and data analytical tools to support their existing knowledge practices to solve complex environmental management problems. We draw on an action co-research project to show how a range of knowledge coproduction mechanisms were developed and applied to weave Indigenous knowledge, artificial intelligence (AI), and technical sources to monitor the health of Nardab, a culturally significant and Ramsar-listed wetland in Australia’s World Heritage-listed Kakadu National Park. The coproduction mechanisms included: holistic assessments of the health of indicators; a dynamic and creative decision-support tool to adaptively manage a complex system; ongoing monitoring and testing of knowledge used for collaborative action; and Indigenous-led governance of research activities and impact at local and regional scales. It was important for local Bininj traditional owners to determine where and how multiple sources of evidence could or should be used and applied to direct and assess on-the-ground actions as part of this collaborative and cross-cultural knowledge sharing and coproduction process. At Nardab, this required negotiating the evidence from qualitative Indigenous-led assessments of significant sites and quantitative ecological information collected and analyzed from cameras and drone surveys. The coproduction mechanisms developed provided a practical and ethical means of empowering different sources of knowledge for adaptive decision making while respecting and protecting differences in how knowledge is generated, interpreted, and applied.

Key Words: adaptive comanagement; codesign; coproduction; digital decision-support tools; ethical artificial intelligence; Kakadu National Park; wetlands

INTRODUCTION

Indigenous peoples’ rights to govern their social-ecological systems and biocultural values are gradually being recognized in domestic and international planning regimes and policies (Garnett et al. 2018, Dawson et al. 2021). However, finding ways to support Indigenous communities to manage the increasing pace and scale of environmental change is challenging (Latulippe and Klenk 2020). Indigenous leaders argue that Indigenous rights, knowledge, and governance systems need to be recognized in collaborative efforts to tackle the many and varied threats affecting the planet’s biocultural ecosystems (Daiyi et al. 2002, Awatere et al. 2017). Hence, many Indigenous groups are seeking to reshape knowledge coproduction processes, practices, and goals to empower Indigenous-led adaptive comanagement of social-ecological systems (Johnson et al. 2016, Austin et al. 2019, Bangalang et al. 2022).

There is now a growing area of research focused on knowledge sharing and coproduction for sustainability that recognizes that knowledge and action are interdependent, and that governance systems influence if and how Indigenous peoples’ priorities, values, and knowledge systems are empowered or marginalized (Dawson et al. 2021). Coproduction frameworks highlight the need to ensure cultural and institutional mechanisms enable “the complementarity of knowledge systems and the values of letting each knowledge system speak for itself, within its own context, without assigning one dominant knowledge system with the role of external validator” (Tengö et al. 2014:580). This includes interest in the “knowledge work” involved for Indigenous, research, and conservation partners to actively expose and negotiate the myriad of tensions that can arise (Robinson and Wallington 2012, Mistry and Berardi 2016, Norström et al. 2020). It also requires attention to how institutional mechanisms influence or privilege certain ways of knowing and acting over others and what this means for Indigenous people, scientists, and a sustainable society (Miller and Wyborn 2020).

Technical knowledge provides precise and quantitative information that is legitimized through scientific methodologies whereas Indigenous knowledge is created and validated through Indigenous protocols and customary practices (Verran et al. 2007, Mistry and Berardi 2016, Carroll et al. 2019). As such, the spiritual and moral attributes of Indigenous knowledge systems require careful conceptual and methodological approaches to ensure...
collaborators involved in knowledge weaving and coproduction processes can reconcile the unique and divergent ways in which Indigenous knowledge is generated, legitimized, and shared (Hudson et al. 2016, Johnson et al. 2016).

The increasing use of big data and analytical modeling to assess and monitor ecosystems offers new opportunities and challenges for creative and ethical multiple evidence-based approaches with Indigenous peoples. Remotely sensed data collected by satellite or unmanned aerial systems and analytical (including artificial intelligence) modeling have provided novel insights into the alarming state of our planet (Kwok 2019, Wearn et al. 2019). These new forms of evidence offer powerful insights, but they are based on knowledge that disconnects data collection, analysis and benefits from the people who own, live on, use, and manage these areas (Lewis et al. 2018, Latulippe and Klenk 2020).

The weaving underpinning knowledge coproduction with data and digital analytical systems can be challenging in Indigenous co-governance regimes in which partners bring a range of perspectives, motivations, and information to the planning process (Abdilla 2018, Austin et al. 2018, Fletcher et al. 2021). Although there can be a broad policy mandate that advocates bringing together a diverse range of knowledge practices and actors for collaborative conservation, there is less agreement on what is needed to best perform the “work” required to negotiate and apply collaborative knowledge-action systems (Schneider et al. 2019, Wheeler and Root-Bernstein 2020). Key mechanisms that result in Indigenous sources of evidence for decision making being assimilated or ignored include disempowering governance mechanisms and planning goals; power dynamics and imbalances between partners; a lack of trust, common ground or common language; and differing opinions about the validity of different knowledge types (Armitage et al. 2011, Alexander et al. 2019).

To help scientists and Indigenous partners negotiate and translate contributions from Indigenous and data analytical sources, an ethical space needs to be negotiated to guide coproduction goals and practices between Indigenous and non-Indigenous partners (Nikolakis and Hotte 2022). This requires Indigenous peoples to be able to position themselves as research leaders and to drive the research agenda (Zurba et al. 2019). The powerful and privileged position of researchers to influence what and with whom they “research” and the impact this has on research partners who engage in and are impacted by the research process also need to be recognized (Maclean et al. 2021). Insights from Indigenous-led and cross-cultural collaborative research practitioners highlight the need for ongoing collaborative work to maintain this ethical space so that Indigenous partners are empowered to negotiate who is making research decisions, how decisions are made, and what partners are learning through the sharing of diverse knowledge contributions and worldviews (Smith 2012).

Indigenous leaders and scholars highlight the importance for coproduction to be managed through Indigenous governance systems when defining this ethical space and propose data collection, curation, analysis, and representation protocol, which respect Indigenous rights and knowledge systems (Walter and Suina 2018, Abdilla et al. 2021). This space also needs to be creative, so Indigenous partners feel culturally safe to engage and experiment with data and analytical models to find new ways to tackle complex issues facing their local social-ecological systems (cf. Johnson et al. 2016, Macdonald et al. 2021).

We draw on this body of work to show how an ethical space was negotiated to develop and apply a range of coproduction mechanisms that enabled the weaving of Indigenous knowledge, AI, and technical data to monitor the health of a social-ecological system with significant biocultural values. The coproduction mechanisms included: holistic assessments of the health of indicators, a dynamic and creative decision-support tool to adaptively manage a complex system, ongoing monitoring and testing of knowledge used for on-the-ground action, and Indigenous-led governance of research activities and impact at local and regional scales. The research process ensured collaborators paid attention to how multiple sources of knowledge were being used and what mechanisms supported a difference in how knowledge was generated, interpreted, and applied to restore Nardab, a culturally significant and Ramsar-listed wetland in Australia’s World Heritage-listed Kakadu National Park.

METHODS

Project design and governance
Kakadu is jointly managed by the Australian Government and its Indigenous traditional owners, collectively known as Bininj in the north of the Park and Mungguy in the south. This project was designed by a Bininj/Mungguy research steering committee (RSC) with traditional owner membership from all the clans in the Kakadu region. The committee was established to guide research approval and activities in this comanaged protected area. The RSC invited a group of non-Indigenous researchers to collaborate on this project to develop and test Bininj and Mungguy healthy Country indicators to guide adaptive and collaborative on-the-ground management actions at selected sites in Kakadu. The four-year research project was supported by Australia’s National Environmental Science Program (https://www.nespnorthern.edu.au/projects/nesp/healthy-country-indicators/).

The aims, objectives, and methods of the research project were approved by the Kakadu Board and received human ethics clearance from the Commonwealth Scientific and Industrial Research Organization (CSIRO, reference number 050/18) and Charles Darwin University (reference number H18055). The RSC chose Nardab as one priority area for this action co-research. Nardab is a significant floodplain area for traditional owners, is a Ramsar-listed wetland of international significance, and lies predominantly in the World Heritage-listed Kakadu National Park (see Fig. 1). Nardab is managed by the East Alligator District Rangers and the Njanjma Rangers, a ranger group based at Kunbarlanja (Gunbalanya), a community to the north-east of Kakadu. Like other areas of Kakadu, Nardab management activities are guided by joint management plans that are implemented under the direction of the Kakadu Board of Joint Management (Australian Government 2016).

The wetlands in Kakadu cover a vast area, much of which is now impacted by weeds, and as such, cost-effective and culturally appropriate approaches to weed management are a priority for joint managers (Adams et al. 2018). Based on Bininj traditional owner and ranger identified values and threats to Nardab, the team agreed to work together to monitor the impacts of para grass (Urochloamutica) on Bininj wetland values. Para grass is a semi-aquatic weedy grass that forms dense monocultures, choking areas of open water and altering habitats and breeding grounds for native species (Adams et al. 2018). Of concern was the impact

https://www.ecologyandsociety.org/vol27/iss4/art136/
of para grass on native food species, including Magpie Geese (Anseranus semipalmata) that use the floodplain to breed, build nests, lay eggs, and raise their young, and long necked turtle (Chelodina rugosa). There was also concern about the impact of para grass on ongoing access to local sites for hunting and gathering that are guided by the six seasons Bininj people use to assess and interact with their Country (cf. Narndal et al. 2015). Traditional owners selected three priority sites within the wetland that contain important hunting, cultural, and social values to focus adaptive para grass management, and monitoring activities.

Bininj healthy Country indicators

The project team worked together to support the identification of Bininj healthy Country indicators and Indigenous-led and holistic ways of monitoring the impacts of para grass on these indicators. Bininj emphasized the need for a pragmatic approach to the identification of indicators, recognizing that Nardab is an important Indigenous biocultural system of their Country and a Ramsar-listed wetland in a World Heritage-listed National Park (Australian Government 2016). Bininj healthy Country indicators were discussed during an initial on-Country visit that resulted in a broad list that was refined during subsequent discussions throughout the action co-research project (for details on workshops and field visits, see Appendix 1). At a follow-up workshop, Bininj articulated the values they wanted to care for at each of the three priority areas and the non-Indigenous researchers demonstrated digital tools that could be used to monitor Bininj healthy Country indicators, such as aerial drones, motion sensor cameras, video cameras, and voice recorders. By the end of the second workshop, five Bininj healthy Country indicators had been confirmed by traditional owners and Bininj rangers: country; community; economic; sharing Indigenous knowledge; and sharing science and Indigenous knowledge.

Methods for collecting evidence to monitor each indicator were identified (see Table 1 for details).

Although agreed forms of evidence were collected for each indicator during each site visit, the first two coauthors interviewed Bininj rangers and traditional owners to assess the health of each of the five indicators. Bininj participants scored each healthy Country indicator using a Likert scale from 1 to 5, where 1 = unhealthy and 5 = healthy and were then asked to describe the rationale behind their assessment. The healthy Country assessments were then discussed as a group including if, what, and why these assessments would trigger action by Bininj, Kakadu rangers and/or the research team. Interviews were also conducted by the first two coauthors throughout the research project with Bininj traditional owners and rangers, reflecting on adaptive management outcomes.

Evidence to monitor and evaluate the five Bininj healthy Country indicators was collected from late 2018 to mid-2021 including prior to para grass management at Nardab in December 2018. Aerial spraying of para grass with herbicide was undertaken at selected sites in 2018 and this was followed up with on-the-ground spraying by Kakadu rangers in 2019-2020. Bininj healthy Country indicators were monitored throughout Bininj seasons until late 2021 (see Appendix 1 for details of monitoring and management activities).
Table 1. Evidence collected to monitor and evaluate Bininj Country indicators.

| Bininj healthy Country indicator | Description of indicator | Evidence collected for each indicator |
|----------------------------------|---------------------------|--------------------------------------|
| Culture                          | The ability of traditional owners and family members to access and connect to priority areas together and the success of hunting trips for culturally important species | Voice and video recordings of traditional owners monitoring Country; Time lapse videos and sound recordings and drone surveys before and after para grass management (see Table 1 for details of all the evidence collected). A digital dashboard was codesigned to weave the evidence collected for the five healthy Country indicators, with the dashboard allowing the knowledge provided to be visualized, assessed, and used in a dynamic and interactive way. |
| Country                          | The health and abundance of culturally significant species, particularly Magpie Geese (*Anseranas semipalmata*), which are an important food species, an indicator of ecosystem health, and are relatively easy to monitor using ecological methods. | Drone surveys at each site were completed before and after para grass was sprayed and for each Bininj season. Members of the research team designed an AI tool to analyze the drone-collected images to produce evidence of the changes in habitat values: para grass, dead para grass, and Magpie Goose habitat (native grass and open water), and the abundance of Magpie Geese (see Appendix 1 for details on how the Healthy Country AI tool was designed and applied). |
| Economic                         | The training and employment opportunities for local Bininj that were generated through the research project. | Quantitative assessments of: the number of people working on the research project; the number of trips where monitoring skills were learned by Bininj participants; the sources of contributions used to pay Bininj participants to be involved in the research project; and the number of times when monitoring skills were practiced by Bininj participants. |
| Sharing Indigenous knowledge     | The knowledge practices that need to be learned and taught by elders and young people and between clan groups. | Quantitative assessments of: the experience levels (junior, mid, and senior) of participants and cumulative numerical assessments of the number of trips to Country with elders and young people for learning and teaching. Photos of elders and young people sharing knowledge on Country were also taken and shared through short trip summaries that were sent back to the ranger station and shared with the local community. |
| Sharing science and Indigenous knowledge | The health of knowledge sharing and coproduction practices of the research team. | Quantitative and qualitative surveys of knowledge sharing and coproduction practice indicators that determined whether research activities were providing negotiated benefits for Bininj; helping to restore and protect agreed values in priority areas; and supporting Indigenous-led collaborative knowledge sharing and research practices (see Robinson et al. 2021b for details). |

Codesigning a digital dashboard to facilitate healthy Country assessments

The evidence collected to monitor each of the five indicators included oral assessments from traditional owners monitoring Country, quantitative assessments of training and employment opportunities for Bininj generated through the project, time lapse videos and sound recordings, and drone surveys before and after para grass management (see Table 1 for details of all the evidence collected). A digital dashboard was codesigned to weave the evidence collected for the five healthy Country indicators, with the dashboard allowing the knowledge provided to be visualized, assessed, and used in a dynamic and interactive way.

The codesign process for the dashboard was done in a workshop in 2019, which was attended by non-Indigenous researchers, traditional owners and rangers. Bininj team members identified important design features of the dashboard, including that the design needed to allow the integrity of all evidence collected to be respected, with oral assessments of healthy Country by traditional owners given the same exposure as quantitative or cumulative numerical assessments of the number of times when monitoring skills were practiced by Bininj participants. The dashboard showed evidence of the team’s collaborative coproduction work and impact, which was monitored through the “sharing science and Indigenous knowledge” indicator. The methods used to do this are described in detail in Robinson et al. (2021b). The focus of this work was to support the local elders with monitoring the knowledge sharing and co-creation process and to provide feedback to the team of non-Indigenous researchers and Kakadu rangers. An Indigenous facilitator supported this feedback process and encouraged elders, researchers, and Kakadu rangers to reflect on how their positionality impacted the ethical and creative space needed for effective engagement, the change processes needed to build or maintain the trust and capacity to manage the uncertainty of these complex social-ecological systems, and the support needed to enact alternative approaches to restore the health of these significant areas. Actions to respond to Bininj feedback were recorded at each workshop and progress on each action was reported back to local elders during the following field trips.

In addition, the dashboard showed evidence of the team’s collaborative coproduction work and impact, which was monitored through the “sharing science and Indigenous knowledge” indicator. The methods used to do this are described in detail in Robinson et al. (2021b). The focus of this work was to support the local elders with monitoring the knowledge sharing and co-creation process and to provide feedback to the team of non-Indigenous researchers and Kakadu rangers. An Indigenous facilitator supported this feedback process and encouraged elders, researchers, and Kakadu rangers to reflect on how their positionality impacted the ethical and creative space needed for effective engagement, the change processes needed to build or maintain the trust and capacity to manage the uncertainty of these complex social-ecological systems, and the support needed to enact alternative approaches to restore the health of these significant areas. Actions to respond to Bininj feedback were recorded at each workshop and progress on each action was reported back to local elders during the following field trips.

Following the dashboard codesign workshops, a digital dashboard prototype was created by non-Indigenous members of the research team and shared with traditional owners, Kakadu rangers and staff, and the Njanjma rangers during field trips in 2019 and 2020. Bininj elders and rangers refined the interactive features of the digital dashboard to allow all the available knowledge provided by the AI tool, time-lapse cameras, video recordings, and on-the-ground survey data to be viewed, assessed, and used as equally important evidence. The dashboard design was further modified by the non-Indigenous research team based on feedback from traditional owners and rangers to ensure the integrity of country-based information while still allowing indicators monitored across different sites in Kakadu to be compared for park monitoring and reporting processes.
The outcomes of the workshops and co-design process highlighted that Indigenous approaches to assess habitat health or management effectiveness are often oral or embedded in Indigenous cultural and knowledge work activities and are difficult to reconcile with quantitative or technical assessments (cf. Zurba et al. 2019, Macdonald et al. 2021). The respectful and equal exposure of multiple forms of evidence ensured that the non-environmental benefits of para grass management (e.g., number of jobs and training opportunities for Bininj tracked through the economic indicator) were highlighted as being of equal benefit and a primary design feature of the dashboard codesign.

Finally, evidence for each Bininj healthy Country indicator needed to be protected and managed through Indigenous data governance protocols so that elders could decide if, when, and how the data should be shared, presented, and used; this required ongoing dialogue and consent (cf. Robinson et al. 2021b). The recent passing of two senior elders and coauthors of this paper means that some of the material has been permanently removed and will be restored in line with cultural practice and the wishes of the traditional owners. Information to be shared publicly on the interactive dashboard is available online (Healthy Country Dashboard 2022).

RESULTS
The methodological approach employed at Nardab resulted in the development and application of four coproduction mechanisms that enabled the weaving of the diverse sources of knowledge needed to adaptively manage this significant area. These coproduction mechanisms included:

- Holistic assessments of the health of indicators;
- A dynamic and creative digital decision-support tool to adaptively manage a complex system;
- Ongoing monitoring and testing of knowledge used for collaborative action; and
- Indigenous-led governance of research activities and its impact at local and regional scales.

Holistic assessments of the health of indicators
The healthy Country digital dashboard presented Bininj all the indicators together and encouraged adaptive learning-based approaches that recognized uncertainty and complexity in what constitutes a desirable or undesirable state of the Nardab wetland. Although conventional approaches advocate the use of monitoring information to trigger decisions based on technical evidence of undesirable ecosystem change (Addison et al. 2016), Bininj assessments of the health of Country indicators enabled traditional owners, rangers, Kakadu staff, and non-Indigenous researchers to reflect on how this evidence could trigger a wide range of actions needed to restore and build the resilience of this social-ecological system (Fig. 2). Details of these Bininj assessments are reported in Bangalang et al. (2022).

Interestingly, Bininj would often argue to continue or enhance management efforts at Nardab when even indicators were assessed as “healthy” (a rating of 4-5) rather than just prioritizing conservation resources and action based on indicators that were viewed as unhealthy (a rating of 1-2). Reflecting on assessments that “sharing Indigenous knowledge” was in a healthy state (rated 4-5), a Bininj elder emphasized in an interview (2018/9/16) the importance of continuing to invest in this activity, because knowledge sharing is just as critical as a healthy ecosystem for restoring and maintaining the health of Nardab:

> We need to keep supporting Elders and young people to keep coming out to learn and share knowledge about Nardab. Knowledge to care for Country is important for Bininj and important to keep this place alive.

When reflecting on the impact of this Indigenous-led collaborative monitoring process, members of the Bininj/Mungguy RSC reflected on how and why Indigenous-led mechanisms to share and test different knowledge to support individual and collective actions in each area worked.

> We worked side by side to share and build new knowledge and new ways to care for our Country and for Kakadu. … This is hard work for us all - we have built the trust and ability to find new ways of working together… these important areas are getting healthier and show the impact of this work (RSC meeting notes, March 2021.)

A dynamic and creative digital decision-support tool to adaptively manage a complex system
Nardab health assessments collected through diverse methods were visualized in a dashboard to provide a platform for Kakadu collaborators to be creative with solutions to restore priority areas. Videos from elder assessments of the health of selected sites were presented alongside evidence collected through drones and time-lapse cameras to show the biophysical changes of this complex system (Fig. 3). Through facilitated workshops, Bininj traditional owners and Kakadu rangers were able to engage in the knowledge work of interpreting, negotiating, and presenting available evidence that showed the rising number of Magpie Geese and the area of para grass removed at a priority site viewed alongside a voice recording of a Bininj elder assessing how para grass management had improved access to hunting sites for Bininj, and a time-lapse video that showed native grasses returning to areas where para grass had once been removed.

The dashboard also offered an innovative mechanism to facilitate ethical and creative collaboration. Ongoing monitoring of the “science and Indigenous knowledge sharing” indicator enabled Bininj collaborators to determine if and how evidence could and should be used, and this built trust between collaborators to find new ways to solve problems, such as building the healthy Country AI tool to enable collaborators to rapidly assess the impact of para grass management efforts (see Fig. 3 and Appendix 2).

Ongoing monitoring and testing of knowledge used for collaborative action
Indigenous-led monitoring of knowledge contributions was an important mechanism to ensure healthy Country assessments were trusted and useable by Bininj traditional owners and Kakadu rangers. Building the quality of knowledge used to inform adaptive comanagement decisions was encouraged through the creative design of the digital dashboard and the monitoring of the “sharing science and Indigenous knowledge indicator” throughout the adaptive management process. Bininj elders
Fig. 2. Holistic assessments of Nardab using Bininj healthy Country indicators enabled Kakadu collaborators to adaptively act, learn, and reflect on actions needed to care for this wetland.

provided feedback on the challenges of assessing the full impact of para grass on significant areas and species, and this prompted the introduction of technical solutions that were codesigned to ensure AI data could be managed and presented using the Bininj seasonal calendar to improve its translation for Bininj use. Additionally, the dashboard’s data system was designed to enable field results to be easily entered and to provide near real time results so that Bininj traditional owners, rangers, and non-Indigenous researchers could view and improve the available evidence while experimenting with on-the-ground adaptive management solutions.

As the evidence from multiple sources emerged and interacted, differences in the knowledge systems that created the data could be iteratively shared and discussed through workshops and conversations in the field. During a field trip in June 2021, traditional owners and Kakadu rangers used the digital dashboard before going onto the floodplain: they listened to traditional owners talking about their assessments on the health of Country; watched time lapse footage of habitat changes of an area after it had been sprayed; reflected on reports of the number of people who had been involved in the project and the opportunities for knowledge sharing between old and young people on Country; and assessed the impact their on-the-ground spraying efforts were having on Magpie Goose numbers and habitat. As a Bininj ranger and elder reflected, when being interviewed about their assessment of each healthy Country indicator (2020/10/28), the evidence not only highlighted increasing numbers of geese and Bininj participants engaging in healthy Country monitoring and management, but that young and old Bininj were engaged in this effort, and that AI and Bininj assessments were working together to show where and why Country was coming back to life:

It is important that our knowledge is shared side by side - this way we can look at all the information we need and work together to decide how we use this to care for Nardab.

Indigenous-led governance of research activities and impact at local and regional scales

The process of coproducing indicators and digital decision-support tools that encompass Indigenous and scientific ontologies for managing Country requires substantial introspection and reflection by collaborators to create the ethical space needed to explore different worldviews and to ensure one knowledge system does not subsume the other. Indigenous governance of how available evidence could or should be woven and used to assess the health of significant sites was critical to facilitate this process. The RSC was resourced to meet regularly to provide regional-scale leadership between Indigenous clan groups, ensuring that knowledge generated from the research could be shared and used in an ethical and equitable manner to care for priority areas and issues across Kakadu. The RSC provided a vital forum for traditional owners to direct how researchers, rangers and park staff would generate and respond to new knowledge and uncertainty; how healthy Country was conceptually and practically framed; and, ultimately, what actions were implemented for Country and its care.
At Nardab, traditional owners were resourced as senior authorities to facilitate and direct Indigenous-led research activities and on-the-ground management actions. These local elder-led processes of assessing Bininj healthy Country indicators led to future-oriented collaboration that required researchers, Kakadu rangers, and park staff to anticipate future ecological change, and to understand the implications of that change for priority Indigenous values (cf. Bangalang et al. 2022). The strong leadership of traditional owners and the RSC also ensured that the appropriate people were consulted and given a chance to collaborate in the research process that led to ongoing consent over what evidence was needed to monitor each healthy Country indicator, how different knowledge contributions would be used and shared, and where surveys and management activities were prioritized.

Both regional and local forums provided useful mechanisms to negotiate and test the coproduction mechanisms developed. The digital dashboard offered a useful mechanism for on-the-ground collaborators to discuss, share, and learn how different sources of evidence could be used to monitor the biocultural landscapes across this World Heritage area. The data agreements underpinning this project mean traditional owners own and maintain authority over their data and decide if, how, and why
aspects of data are used to guide conservation decisions and actions. Short videos of the project were cocreated and shared so that the broader Bininj/Mungguy community were kept informed of project activities and impacts (see Bininj Mungguy healthy Country indicators for Kakadu National Park). The research team also regularly copresented project updates to Kakadu and government agency staff, including discussions that focused on how this approach to monitoring healthy Country could be supported by existing park reporting tools and requirements.

DISCUSSION
There is growing interest in the codesign, testing and application of practical mechanisms to visualize and use different sources of knowledge to adaptively manage significant biocultural landscapes that empower Indigenous people and guide effective on-the-ground action and impact. In Kakadu, this process was supported by Indigenous-led governance arrangements at local and regional scales and facilitated a codesigned digital dashboard system that enabled knowledge from Bininj, technical data, and AI analytics to be shared in an ethical and creative way. Guided by Bininj healthy Country indicators, divergent sources of evidence interacted to enable Kakadu collaborators to dialogue with available data through a process that was not focused on a single solution to a problem but enabled different evidence to inform what was needed to restore and enhance the health of this unique biocultural wetland.

Elsewhere, there has been some progress in considering the ethical requirements for data and data analytical systems to be trusted and trustworthy by decision makers. This included consideration of best-practice data collection, curation, algorithm design, and analytics (e.g., Kwok 2019, Morley et al. 2021). However, Indigenous leaders highlighted that less is known about if and how these ethical principles correlated with Indigenous knowledge governance systems and ethical standards (Abdilla 2018, Walter and Suina 2018). The ethical space traits and characteristics articulated by Nikolakis and Hotte (2022) reflect the criteria by which Bininj reflected on the “sharing science and Indigenous knowledge” indicator and highlight the importance of coproduction mechanisms to guide this effort. Maria Lee, previous Chair of Kakadu Board of Management, eloquently describes the ethical space that was created by this collaboration:

*We’ve worked hard to build this relationship and we want to keep working with you. This NESP team brings Bininj to life here, they feel good about themselves because you motivate them. You did a good job; our young people are happy, and I want to see it keep going so we can keep motivating our young people.*

Building strong relationships was supported by an ongoing dialogic process by which knowledge was shared, combined, and used to restore the health of each biocultural landscape. As Nikolakis and Hotte (2022) noted, this ethical space also required active listening, respect, introspection, and reflection, which was supported by Bininj elders and rangers providing on-going monitoring of research activities and impact. Bininj collaborators valued creativity as part of this process, provided non-Indigenous collaborators ensured science and technical evidence was not treated as superior to Indigenous knowledge practices (cf. Nikolakis and Hotte 2022). The introduction of drones to help “see Country from the sky”, motion cameras to monitor “changes to Country when we are not there,” and the AI analysis, which provided rapid assessment of each area to guide on-the-ground weed spraying activities were valued because Bininj cultural protocols had directed why and how data were collected, managed, and used (cf. Macdonald et al. 2021).

As Bangalang et al. (2022) observed, it is important to support a dialogue rather than a monologue between knowledge systems, guided by moral authority and ethical reasoning that connect kin and Country and is governed through Indigenous law. The production of the digital dashboard in Kakadu supported Bininj traditional owners, Kakadu rangers and staff, and non-Indigenous researchers in their efforts to interact and provide feedback on the quality and purpose of diverse sources of evidence being used. It continued to be important that this approach to assess healthy Country at Nardab remain open to feedback and refinement to ensure Bininj can direct activities on the floodplain.

As one of our Bininj coauthors rightly noted, data themselves cannot be engineered to be trustworthy, ethical, or creative, and so it is essential that Indigenous people lead each step of the data collection, analysis, and translation process because AI does not know how to use this information the right way, it’s up to the Bininj to guide the way. At Nardab, trust built between partners supported a collaborative and adaptive process to test and validate multiple sources of evidence while Kakadu collaborators adaptively managed this unique wetland. This creative process of experimentation, learning, and adjustment relied on ongoing dialogue between Bininj, between Bininj and scientists, and between Bininj, scientists, and Kakadu rangers and staff who respected differences in how knowledge is generated, interpreted, and applied.

Indigenous governance processes established at local and regional (park wide) scales were essential to ensure the coproduction mechanisms could support on-the-ground and park-wide adaptive comanagement efforts (cf. Austin et al. 2019). The Bininj healthy Country indicators and monitoring system can now be incorporated into Kakadu National Park performance reporting activities and obligations. This would require significant skills, digital infrastructure, and investment, especially if this approach is to be applied to other places with different values and threats in this World Heritage area. On-the-ground management research activities at Nardab have been restricted since the outbreak of COVID-19 and the death of two senior elders. Further resources have been secured to provide AI and digital training to Bininj rangers to support this work. Institutionalizing Indigenous-led adaptive decision-making processes will need all collaborators to be held accountable to these coproduction processes.

CONCLUSION
Over the last decades, the pressing challenges facing adaptive co-governance of social-ecological systems have seen a diversity of knowledge weaving and coproduction frameworks emerge that draw on Indigenous knowledge and environmental stewardship systems, data analytical tools, and digital visualization platforms (Tengo et al. 2014, Austin et al. 2019, Zurba et al. 2019). These emerging digital analytical capabilities and technologies have generated demand for ethical and creative spaces for Indigenous
people to lead research and planning agendas to ensure multiple
evidence-based, decision-making support their own agendas for
communities and Country, rather than the choice and quality of
evidence used to assess the health of social-ecological condition
being contained in a “black box” of non-Indigenous scientific
framing. Indigenous groups are offering new ways to codecision
knowledge-action systems and interactions in terms of
Indigenous values, rights, and responsibilities for their Country.

Coproduction mechanisms can facilitate the dialogue needed to
ensure ontological, creative, and ethical considerations can guide
how knowledge derived from Indigenous, digital, and AI sources
can be appropriately tested and translated to inform on-the-
ground decisions. As the experience at Nardab highlights,
coproduction mechanisms can be designed to ensure Indigenous
people, researchers, and conservation partners feel culturally safe
to experiment and learn about what evidence is useful and trusted.
Key to this effort is that local Indigenous collaborators are
resourced and empowered to make decisions about how
knowledge from new data and AI analytical systems can support
Indigenous-led adaptive decision making.

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Data Availability:

For data and material related to this project see https://www.
nespnorthern.edu.au/projects/nesp/healthy-country-indicators/

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Appendix 1. Details of para grass monitoring and management activities at Nardab wetland throughout the research project.

| When       | Who                                                                 | What                                                                 |
|------------|----------------------------------------------------------------------|----------------------------------------------------------------------|
| 4-5/12/18  | Two *Bininj* Kakadu Rangers, one non-Indigenous Kakadu Ranger, eight Njanjma Rangers, two non-Indigenous Njanjma coordinators, and two non-Indigenous researchers. | Qualitative and quantitative monitoring of *Bininj* healthy Country indicators |
| 07/12/18   | One Traditional Owner/Kakadu Ranger, two *Bininj* Kakadu Rangers, three Njanjma Rangers, two non-Indigenous Njanjma coordinators, two *Bininj* and one non-*Bininj* Kakadu staff members in the weed management team, and two non-Indigenous researchers | Aerial application of herbicide on para grass in priority areas |
| 21/03/19   | One Traditional Owner/Kakadu Ranger, two *Bininj* Kakadu Rangers, one Indigenous Kakadu staff member, and one non-Indigenous researcher | Qualitative monitoring of *Bininj* healthy Country indicators |
| 03/04/19   | One *Bininj* Kakadu Ranger, two Indigenous Kakadu staff, and three non-Indigenous researchers | Quantitative monitoring of *Bininj* healthy Country indicators |
| 27/06/19   | Two Traditional Owners/Kakadu Rangers, one non-*Bininj* Kakadu Ranger, two non-Indigenous Kakadu staff members, two non-Indigenous researchers | Qualitative monitoring of *Bininj* healthy Country indicators |
| 13/08/19   | Two Traditional Owners, two Traditional Owners/Kakadu Rangers, one *Bininj* Kakadu Ranger, two non-*Bininj* Kakadu Rangers, three Njanjma Rangers, one non-Indigenous Njanjma coordinator, five non-Indigenous researchers | Qualitative and quantitative monitoring of *Bininj* healthy Country indicators |
| 16/09/19   | Two Traditional Owners/Kakadu Rangers, one *Bininj* Kakadu Ranger, two non-*Bininj* Kakadu Rangers, one Qualitative and quantitative monitoring of |
| Date       | Description                                                                 | Action                                                                 | Notes |
|------------|-----------------------------------------------------------------------------|------------------------------------------------------------------------|-------|
| 11/10/19   | One non-*Bininj* Kakadu Ranger                                               | On-ground application of herbicide on para grass in priority areas     |       |
| 14/10/19   | One non-*Bininj* Kakadu Ranger                                               | On-ground application of herbicide on para grass in priority areas     |       |
| 28/10/19   | Four Traditional Owners, one Traditional Owner/Kakadu Ranger, one non-*Bininj* Kakadu Ranger, two Njanjma Rangers, one Indigenous and one non-Indigenous Kakadu staff members, one Indigenous and four non-Indigenous researchers | Qualitative and quantitative monitoring of *Bininj* healthy Country indicators |       |
| 29/10/19   | Two Traditional Owners/Kakadu Rangers, one non-*Bininj* Kakadu Rangers, four non-Indigenous researchers | Qualitative monitoring of *Bininj* healthy Country indicators           |       |
| 01/11/19   | One non-*Bininj* Kakadu Ranger                                               | On-ground application of herbicide on para grass in priority areas     |       |
| 05/11/19   | One Traditional Owner/Kakadu Ranger, one non-*Bininj* Kakadu Ranger          | On-ground application of herbicide on para grass in priority areas     |       |
| 07/02/20   | One non-*Bininj* Kakadu Ranger                                               | On-ground application of herbicide on para grass in priority areas     |       |
| 26/05/20   | Two Traditional Owners/Kakadu Rangers                                        | On-ground application of herbicide on para grass in priority areas     |       |
| 07/07/20   | One non-*Bininj* Kakadu Ranger                                               | On-ground application of herbicide on para grass in priority areas     |       |
| Date     | Description                                                                 | Participants                                                                                       |
|----------|------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------|
| 23/09/20 | On-ground application of herbicide on para grass in priority areas           | One non-Bininj Kakadu Ranger                                                                    |
| 28/10/20 | Qualitative and quantitative monitoring of Bininj healthy Country indicators | Two Traditional Owners, three Traditional Owners/Kakadu Rangers, two Bininj Kakadu Rangers, two Njanjma Rangers, three non-Bininj Kakadu Rangers, one Indigenous and one non-Indigenous Kakadu staff members, one Indigenous and two non-Indigenous researchers |
| 12/07/21 | Qualitative and quantitative monitoring of Bininj healthy Country indicators | One Traditional Owner, two Traditional Owners/Kakadu Rangers, one Bininj Kakadu Ranger, three Indigenous Kakadu staff members, one Indigenous and one non-Indigenous staff members |
Appendix 2. The Healthy Country Artificial Intelligence (AI) tool.

Under the direction of Bininj Traditional Owners, the research team co-designed the Healthy Country AI tool to provide rapid assessment of Indigenous-directed adaptive weed management activities. Bininj elders were clear that this Healthy Country AI contribution needed to be both ethical and useful. This meant that data collection and analytical efforts needed to be governed by Traditional Owners; reflect the priority areas of concern for local Bininj; respond to the seasonal aspects of Bininj stewardship of their estates; and support on-ground adaptive co-management efforts. Bininj collaborators also asked that the Healthy Country AI tool was made freely available so that other Indigenous groups could use this tool (Robinson et al. 2022).

Survey methodology for data collection

Drones flown over selected sites captured footage of Nardab before and after on-ground para grass management, with the footage used as data for the AI models. Drone surveys were chosen as methodology for several reasons. Ecological surveys on northern Australian floodplains are notoriously challenging due to resident saltwater crocodiles, which are dangerous and difficult to see amongst the water and vegetation (cf. Inman et al. 2019). Drones can also collect accurate and visually appealing wildlife and habitat monitoring data at large scales (Hodgson et al. 2018, Rees et al. 2018). Additionally, drones can decentralise data acquisition (Koh and Wich 2012) and provide data collection employment and training opportunities for local people (Vargas-Ramirez and Paneque-Gálvez 2019).

The drone surveys were done on sites chosen by Bininj elders and reflected areas that had important local Indigenous and conservation values (see Bangalang et al. 2022). At each priority site, non-Indigenous researchers, Traditional Owners and Rangers worked together to map the boundaries of an area where the drone could fly, and where the drone would not fly (e.g. near culturally sensitive sites). Traditional Owners were always consulted and/or on Country during drone surveys to ensure the ethical protocols for drone use were upheld (see Macdonald et al. 2021). The mapping exercise ensured the survey area was large enough to capture ecological processes but small enough to be flown by a drone within a reasonable time frame to fit in with Bininj and ranger day-to-day work schedules (limited to 60 minutes flight time and less than 30 hectares).
A fixed set of transects were programmed into the drone to cover the same area of interest at the same height (60 metres above the ground) each time the area was flown. Regular transects were derived using DroneDeploy software (https://www.dronedeploy.com) to cover the survey area with a 75% front overlap and 65% side overlap between photos, to allow photogrammetric analysis. The flight speed and direction were optimised by the software. DroneDeploy was operated through a mobile device, with the drone automatically flying the pre-programmed transects. Flights were undertaken within line-of-sight of two trained operators (Perry and May), one ready to control the drone and the other spotting for birds of prey or low flying aircraft.

**Curation of drone collected data**

Drone collected data was downloaded using DroneDeploy, the images are stitched and geo-rectified into geotiffs (image file that embeds georeferencing information). Bininj people use six seasons to assess annual changes in Country indicators and so the Kunwinjku seasonal calendar was used to guide drone survey schedules so that sites were monitored in: Kunumeleng (December) 2018; Bangkerreng (April) 2019; Wurrkeng (August) 2019; Kurrung (September) 2019; Kunumeleng (late October) 2019, Kunumeleng (late October) 2020 and Wurrkeng (July) 2021. This seasonal calendar was also used to design data management mechanisms. Drone collected photos stitched and geo-rectified were separated and stored in a hierarchical folder structure that includes site, season, date and time. This provides a unique identifier for logging results. Survey data was stored on an Azure cloud data storage resource.

**Artificial Intelligence analytical design**

To support the automation of drone collected data the Healthy Country AI model was designed to analyse changes in habitat values and the distribution and abundance of magpie geese within habitat categories. The Healthy Country AI model consists of three models developed using Custom Vision and Azure Machine Learning Service:

- Para grass (classification, 304 × 228 tiles) (Custom Vision)
- Magpie geese (object detection, 304 × 228 tiles) (Custom Vision)
- Para grass (semantic segmentation) (Azure Machine Learning Service)
Once the geotiffs are uploaded, an automated function breaks the geotiff into small tiles (304 x 228). This reflects around 120 individual tiles for each photograph. The tiles are automatically transferred to customvision.ai for training. The function sends tiles to pre-prepared site-season projects that duplicate the tiles in two projects, one for object detection and the other for classification.

To develop an accurate model, each category requires many labels. This means habitat models are a trade-off between specificity (e.g. 10 categories to describe the different growth states of para grass) and generality. For example, if the aim is to obtain a minimum of 2000 labels for each category, five categories will require 10,000 labels. Conversely, the selection of more general and inclusive labels (e.g. lump all types of grass into an "all grasses" label), fewer labels will be required, but the model will be less specific.

Object detection models require labelling of individual animals within the tiled image (Figure A1). For the habitat model, a subject matter expert labelled all bird species that were easily identified in the tiles. The focus species, magpie goose, was easily separated from other species so there was a very high confidence in these labels. Other species, such as egrets, terns and spoonbills, were less distinct (from 60 m) and were lumped into a single category which included all white birds. Several other species had very few individuals (<15 labels) and these were excluded. Labels were dominated by magpie geese and white birds; the remaining species were sparse.

**Fig. A2.1.** From left to right, examples of object detection labels for mixed species, crocodile and magpie geese.

For the habitat model, the dominant habitat type for each tile was scored by season and site (see Figure A2). The complexity of the labelling task was reduced by limiting the labels to broad habitat types, with more detail provided for target species, para grass, including a “dead para grass” label and a “recovering para grass” label which directly related to the management goals of the Rangers and Traditional Owners. A single tag per image was used for the classification model. This required
the involvement of subject matter experts, in this case researchers with good knowledge of the visual characteristics of para grass compared with other native species from aerial photos. Using this method, it was necessary to make decisions about which habitat type was dominant, reducing the complexity of the labelling task but also reducing the detail of the results and leading to difficult labelling decisions in tiles that had diverse habitat characteristic, e.g. bare ground, water lilies, dead para grass, dense para grass, other grass or water dominated.

Fig. A2.2. From left to right, examples of para grass dominated, water dominated, water lily dominated tiles.

Azure Custom Vision was used to provide a cognitive service to build, deploy, and improve image classifiers. An image classifier is an AI service that applies labels (which represent classes) to images, according to their visual characteristics. The Custom Vision Service uses labels to calculate the precision and recall of training iterations using k-fold cross validation process. After each training iteration, precision, recall and mean average precision are reported as a means of objectively assessing the performance of the model, given the expanded label set. Precision indicates how well the model predicted values based on the training set. For example, if we labelled 100 magpie geese and the model predicted that there were 99 magpie geese then the precision would be 99%. Recall indicates the fraction of actual classifications that were correctly identified. For example, if there were 100 images of apples, and the model identified 80 as apples, the recall would be 80%.

**Scoring function and data summaries**

Labelling and model training were completed iteratively until precision and recall was sufficient to closely reflect the observed values as defined by subject matter experts. Accurate predictions required thousands of tagged images spread across the available categories. A scoring function was
pointed to the customvision.ai project endpoint and model weights were used to predict the habitat classification and number of each species for every tile in the surveys.

Scored values were stored in a database and included summary fields such as survey date, season, latitude, and longitude of the centre of each tile, extracted from the geotiff. The predicted habitat and species counts were recorded in the database along with the certainty value (0-100%). This provided a spatio-temporal data set that could be summarised and visualised to support adaptive management and planning. A link to the location of the scored tiles is recorded in the database including an access token that allows the photo to be visualised in a dashboard.

Data security was managed through firewall settings in the cloud server restricting access to individual computer IP addresses so that Bininj could manage data according to local knowledge sharing protocols. This effectively excluded any external access to the data unless the administrator allowed it and empowered Bininj to manage if Healthy Country AI model outputs would be shared with collaborators.

Separate tabs were also created for each survey and each season. We used the MapBox custom visual (https://docs.mapbox.com/help/tutorials/power-bi/) to visualise and interact with the geotiff at full resolution. We linked the latitude and longitude of the predicted values to the map through this visualisation. Habitat values were displayed using a tree map that produced uniquely coloured, proportional rectangles based on the contribution of each habitat category to the total. This analysis was incorporated into the digital dashboard using local language and symbols that could be easily translated by Bininj collaborators.

While the Healthy Country AI tool makes a first step towards ethical AI supported by Indigenous knowledge coproduction it only a start. Magpie geese were chosen by Bininj as an indicator species of the health of Nardab because these birds are culturally significant. This was discussed with the non-Indigenous research team who agreed with the choice as these birds are easy to identify and label. This meant there were no dilemmas in the labelling but it only provides a partial insight into the impacts of para grass management on the health of Nardab wetlands. The next step of this process to train rangers under the newly established Healthy Country AI and digital training program
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