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Using natural capital accounting for biodiversity offset policy: a case study from the Australian Capital Territory

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ABSTRACT

Biodiversity offsetting aims to balance biodiversity conservation against demand for land required for development, while natural capital accounting (NCA) is an information system for integrated environmental-economic decision-making. Many countries use both, but to date, NCA is untested for biodiversity offset policy. We rectify this using the Australian Capital Territory (ACT), a subnational jurisdiction using offsetting and facing global challenges common to offset implementation and biodiversity conservation. Hybrid land cover, land use and ecosystem extent accounts for offset areas, development areas, and protected areas were produced for 2010 to 2020. These identified 2217 ha of offsets required for 26 developments, mainly impacting natural temperate grasslands (NTG) and box-gum grassy woodlands (BGGW). Assessing net biodiversity changes was challenging because changes in ecosystem extent based on land cover are open to interpretation, and ecosystem condition accounts couldn't be produced. Between 2010 and 2020, land cover associated with NTG and BGGW declined across the ACT: 3011 ha fall in BGGW-short vegetation and 5761 ha fall in BGGW-open woodland. ACT offset areas were typically within land zones unlikely to be developed, and the area for new offsets is limited (9828 ha). While the data challenges of assessing offset policy identified in this study and others are a barrier to account production and use for offset policy, we conclude that accounting could inform offset policies in the ACT and globally by systematically linking biodiversity offsets to ecosystem extent and condition, allowing consistent net biodiversity changes assessment and providing a path to international standardisation of offset measurement and reporting.

1. Introduction

Global biodiversity decline has led to policies to limit the impacts of human development (IPBES et al., 2019). Biodiversity offsetting is one such policy and is designed to compensate for the loss of biodiversity resulting from development by creating, restoring, or protecting species or habitats elsewhere (Maron et al., 2015; Peterson et al., 2018; Pope et al., 2021). The aim of offsetting is "no net loss" or "net gain", meaning that after development, there is as much or more biodiversity (species and habitats) as there was before development (Bull and Milner-Gulland, 2020). This approach to biodiversity conservation appeals to governments and the private sector because it removes an obstacle to economic growth while theoretically meeting conservation objectives (Bull et al., 2013) but remains controversial (Maron et al., 2016).

Biodiversity offsetting has been criticised for failing to effectively compensate for biodiversity losses and for lacking transparency and accountability (e.g., Bull et al., 2018; Grimm and Köppel, 2019; Grimm, 2020). Few biodiversity offset programs routinely collect or report sufficient data to enable the effectiveness of the policy or its implementation to be evaluated (e.g., Carver and Sullivan, 2017; Gibbons et al., 2018; Kujala et al., 2022). zu Ermgassen et al. (2019) reviewed 32 offset programs worldwide, finding that most programs lacked data to evaluate effectiveness, and only a small proportion of those with adequate data demonstrated no net loss. A lack of evidence leads to reduced public confidence in biodiversity offsetting, undermining its objective of

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biodiversity conservation (Gordon et al., 2015). Offsetting schemes would clearly benefit from a structured information framework and standardised and regular reporting.

Natural capital accounting (NCA) provides such a framework. NCA is an umbrella term for many initiatives and is standardised in the System of Environmental-Economic Accounting (SEEA) (UN, 2014; UN, 2024), which links to the System of National Accounts (EC, 2009). The SEEA is designed to support decision-making by integrating diverse sources of environmental and economic data (Vardon et al., 2016). The SEEA is described in Section 1.2. In response to the call by Bull et al. (2020) for "net positive outcomes for nature", Burnett et al. (2020) suggested that the SEEA would be an effective monitoring tool for "nature-positive" development, noting that the SEEA is a flexible system that could be used at any scale.

Using an Australian case study, we test the ability of NCA to be used to support biodiversity offsetting policy. Until now, no attempt has been made to do this in Australia or elsewhere. A theoretical case for its application in the private sector has been made by Dickie et al. (2018). An Australian case study is possible because Australia uses biodiversity offsetting (Australian Government, 2012) and advocates producing and using natural capital accounting for decision-making (Samuel, 2021).

The following subsections outline the study's aim and research questions, the case study area and the reasons for its selection, Australian biodiversity offset laws, the SEEA, and how biodiversity conservation could be informed by the SEEA (Sections 1.2 to 1.4). Following the Introduction are the Data sources and methods (Section 2), Results (Section 3), Discussion (Section 4), Conclusions (Section 5) and References (Section 6).

1.1. Study aim and research questions

This study aims to test the ability of SEEA to support biodiversity offset policy and management, using a case study from the Australian Capital Territory (ACT). The ACT is a small (2358 km^2) rapidly growing (ABS, 2023), subnational jurisdiction within Australia that has applied the same biodiversity offset policy over the period of this study (2010–2020), maintains records of biodiversity offsets and, because it occupies a relatively small area, is relatively well serviced with consistent spatial data that are necessary to apply SEEA. The ACT employs a biodiversity offset policy that is consistent with the Australian Government's (ACT Government, 2015). The ACT faces challenges common to many parts of the world attempting to balance the ongoing demand for land for development with environmental objectives such as biodiversity conservation (OCSE, 2024). SEEA-based accounts for the ACT have been produced by the government (Smith et al., 2017) and academic researchers (Bond and Vardon, 2023; Chen et al., 2023; Chen and Vardon, 2024), and these accounts provide a foundation for additional research on the applications of NCA to decision-making. These factors make the ACT a good candidate for testing the ability of accounting to inform offset policy.

To test the ability of SEEA to support biodiversity offset policy, we pose three questions.

(1) Can SEEA-based accounts suitable for biodiversity offset policy be produced for the ACT?
(2) What do the accounts reveal about biodiversity offset policy in the ACT?
(3) How can the SEEA address common challenges with biodiversity offset policy?

Producing all the accounts that could benefit biodiversity offset policy is a significant undertaking and beyond the resources available for this study. As such, the scope of the study was limited to land cover, land use, and ecosystem extent accounts. Ecosystem condition accounts were also deemed in scope but unable to be produced for lack of data (see Section 2.5).

1.2. Case study area: Australian Capital Territory (ACT)

The ACT is in the south-east of Australia. Land use in the ACT is 55 % nature conservation, 21 % grazing modified pastures, and 13 % urban intensive uses (ABARES, 2022). Like many jurisdictions around the world, the ACT Government endeavours to minimise biodiversity loss while providing the space needed for development (e.g., ACT Territory Pan, 2023,[1] EPSDD, 2023). Between 2007 and 2011, 75 % of the area allocated for residential development was greenfield, and 25 % was urban infill (OCSE, 2015). Most native vegetation clearance in the ACT occurs due to urban expansion (OCSE, 2019). The small area of the ACT means the area available for new developments and offsets is limited.

1.3. Offset policy in the ACT

The ACT Government applies the Australian Government's environmental offset policy (DSEWPC, 2012). The policy applies only to protected matters (i.e., nationally threatened species or ecological communities) listed on the Australian Government's Environment Protection and Biodiversity Conservation (EPBC) Act 1999.[2] Where a development is assessed by the Australian Government's Minister for the Environment to have a significant impact on 'matters of national environmental significance' (MNES), the proponent or developer must provide a biodiversity offset that improves or maintains the protected matter, which is equivalent to no net loss or net gain. An offset site is the area in which biodiversity is required to be improved or maintained to compensate for the impact of developments affecting MNES.

Among the principles that underpin the policy, offsets must only be applied to residual impacts after the mitigation hierarchy (avoid, mitigate, offset) has been applied, must be additional to actions that are already required by law or policy, must be equivalent (or like-for-like) and must be predominantly direct offsets (DSEWPC, 2012). Most biodiversity offsets in the ACT have been applied as part of strategic assessments of large residential areas that impact several protected matters and involve the establishment of multiple biodiversity offsets. Strategic Assessment areas are areas that were subject to landscape scale assessments endorsed under the EPBC Act.[1] Such assessments can help to address issues such as "cumulative impacts on matters of national environmental significance (MNES) protected by the EPBC Act" (DoE, 2013). Strategic Assessment areas are listed in the ACT Government Offset Register and include offset areas managed by the ACT Government. The ACT is unusual because the government's Suburban Land Agency is the proponent for most developments and most biodiversity offsets are added to the formal protected area network.

The offset policies are made under Australia's national and State/Territory (subnational) laws that have distinct, though overlapping, legal responsibilities for biodiversity. The national regime is the EPBC Act. The ACT's is in the Nature Conservation Act 2014 [3] (ACT) and the Planning Act 2023,[4,5]; the former contains broad provisions for biodiversity conservation while the latter provides for the assessment and approval of development proposals, including those impacting biodiversity. In the event of any inconsistency between these regimes, Australia's Constitution provides that the national laws prevail. Under an agreement between the two governments, where a development in the ACT requires approval by both jurisdictions, a single assessment is prepared under the supervision of the ACT government. Although a

[1] The Territory Plan is an ACT law https://www.legislation.act.gov.au/ni/2023-540.

[2] EPBC Act http://www.austlii.edu.au/cgi-bin/viewdb/au/legis/cth/consol_act/epabca1999588/.

[3] The Conservation Act (ACT) https://www.legislation.act.gov.au/a/2014-59.

[4] The Planning Act (ACT) https://www.legislation.act.gov.au/a/2023-18/.

[5] The Planning Act replaced the Planning and Development Act 2007.

separate approval is still required from each government, approval conditions are usually aligned. The Australian Government determines the nature of the offsets required and an online Offset Assessment Guide[6] is available includes factors like extent and condition of ecosystems or species habitats impacted by developments to calculating offsets.

Two ecological communities in the ACT are listed as critically endangered under the EPBC Act 1999 [7]: White Box-Yellow Box-Blakely's Red Gum Grassy Woodland and Derived Native Grassland or Box-Gum Grassy Woodland (BGGW) for short, and the Natural Temperate Grassland of the South Eastern Highlands (NTG).[8] The ACT is important for the protection of BGGW as it contains the largest remnants that are in good condition (DEH, 2006) and is one of a few regions where BGGW extent is relatively stable (Vardon et al., 2023). Only about 5 % (1000 ha) of the pre-settlement extent of NTG in the ACT remains in moderate to good condition (Lynch, 2022).

There has been criticism of biodiversity offset policy, implementation and compliance in Australia and elsewhere (e.g. Maron et al., 2016; Bull et al., 2018; Gibbons et al., 2018; Pope et al., 2021; Samuel, 2020; DPE, 2023; Evans, 2023). The criticisms are many and include offset definition and purpose, metrics and monitoring, poor compliance and enforcement. For example, an audit of 222 development approvals under the environmental offset policy commissioned by the Australian Government, 14 % were non-compliant and in a further study of 120 approved developments, 25 % had not secured the necessary offsets (DCCEEW, 2024). Further, the Australian Government does not report on the extent to which the policy meets its key objective: to improve or maintain environmental outcomes for protected matters. Thus, a mechanism that accounts for, and reports on, losses and gains under the environmental offset policy is urgently needed.

1.4. System of Environmental-Economic Accounting (SEEA)

The SEEA is an international statistical standard developed under the auspices of the United Nations. The SEEA has two main parts, the Central Framework (SEEA CF) (UN, 2014) and Ecosystem Accounting (SEEA EA) (UN, 2024). The SEEA EA is being used in 37 countries (Edens et al., 2022). The SEEA EA complements measuring the relationships between the environment and the economy described in the SEEA CF. The SEEA EA focuses on ecosystems, tracking their extent, condition, and the services they provide, using consistent concepts and classifications to produce a suite of standardised, interlinked, and spatially referenced accounts (Fig. 1). The SEEA CF measures environmental pressures such as pollution and resource extraction, individual resource stocks like forests and water, and environmental responses in the form of expenditures, taxes, and subsidies. It includes accounts for land cover and land use. Together, these systems provide a comprehensive view of environmental-economic relationships, illustrating how the environment and ecosystems support the economy and how economic activities impact the environment and ecosystems.

SEEA accounts accommodate a "plurality of metrics" (Obst and Vardon, 2014), and the SEEA is well-suited to biodiversity assessment (Burnett et al., 2020). Accounts can use physical (e.g., ha, no. of species, parts per million) or monetary (e.g., $) metrics. While monetary accounts can be produced, the objective of SEEA-based accounting is not monetisation. Ecosystem accounting can be applied at different levels of government, by individual companies, industries (e.g., agriculture, mining, manufacturing, etc), and at different spatial scales (e.g., national, regional, and local) (UN, 2024). Ecosystem accounts are compiled for ecosystem accounting areas, which can be based on biophysical (e.g., water catchments) or administrative boundaries (e.g., nations, subnational jurisdictions, or particular land uses like protected areas).

The SEEA EA includes accounting for biodiversity, and biodiversity is an indicator of ecosystem condition (UN, 2024; King et al., 2021). Several studies have addressed the theory and practice of biodiversity accounting, with case studies developing species-level biodiversity accounts (e.g., Keith et al., 2017; Bond and Vardon, 2023; Bogaart et al., 2020), summaries of the theoretical and practical aspects of biodiversity accounting (Vardon et al., 2019; Burnett et al., 2020; UN, 2020; King et al., 2021), and forest and protected area management (King et al., 2023, 2024; Maes et al., 2023) Ecosystem accounting was used to investigate how effectively an endangered ecosystem was protected under the Australian EPBC Act (Vardon et al., 2023).

Ecosystem accounting can benefit biodiversity conservation policies (UN, 2020; King et al., 2023). This could be at the site level (e.g., individual farms, development or offset areas), the landscape in which these sites occur or nationally. For example, ACT conservation policies and plans were mapped to accounting by Chen et al. (2023), and Normyle et al. (2024) systematically reviewed 97 articles on biodiversity offsetting to assess how the SEEA might theoretically address common criticisms of biodiversity offsetting. The five most common issues identified in the review were institutional guidance, definition and purpose, metrics and data, spatial planning, and enforcement and compliance.

2. Data sources and methods

Land and ecosystem extent accounts and condition accounts were attempted to address the research questions. This was to spatially link information on development approvals, offset areas, and land planning to biodiversity conservation and net changes to biodiversity.

To do this various data sources and methods were investigated and used to produce accounts for the ACT. Offset and development areas were identified from administrative sources (Section 2.1). Many data sources on land cover, land use, land zoning, and ecosystem extent were identified (Sections 2.2 to 2.4; Table 1). Data on ecosystem condition was not sufficient for account production (Section 2.5). The data used are described in more detail the sections that follow.

2.1. Offset, development and strategic assessment areas

In this study, the offset, development and strategic assessment areas are the Ecosystem Accounting Areas of interest. We identified biodiversity offset areas and corresponding development sites impacting MNES using the EPBC Offset Register[9] administered by the Australian Government's Department of Climate Change, Energy, the Environment and Water (DCCEEW), and the ACT Government's Offset Register[10] until October 2022 (Supplementary Information Table S1). For several EPBC Act referrals, spatial data on the location of the offset or corresponding development site (or both), were missing, hence noted as 'unknown' in the study database (see Supplementary Information Table S2). For some sites, the written description of offsets and corresponding development areas enabled us to generate a spatial approximation of the site area.

The EPBC Offsets Register recorded 26 developments approved on the condition of biodiversity offsets in the ACT (Supplementary Information Table S1). Thirteen of the development projects approved with offsets recorded in the EPBC Offsets Register were also recorded in the

[6] https://www.dcceew.gov.au/environment/epbc/approvals/offsets/guidance/offsets-assessment-guide.

[7] The Environment Protection and Biodiversity Conservation Act 1999 is an Act of the Parliament of Australia that provides a framework for protection of the Australian environment and heritage, including its biodiversity and its natural and culturally significant places.

[8] EPBC Act List of Threatened Ecological Communities https://www.environment.gov.au/cgi-bin/sprat/public/publicookupcommunities.pl.

[9] https://epbcpublicportal.awe.gov.au/offsets-register/.

[10] https://www.planning.act.gov.au/professionals/sustainable-development/offsets-register.

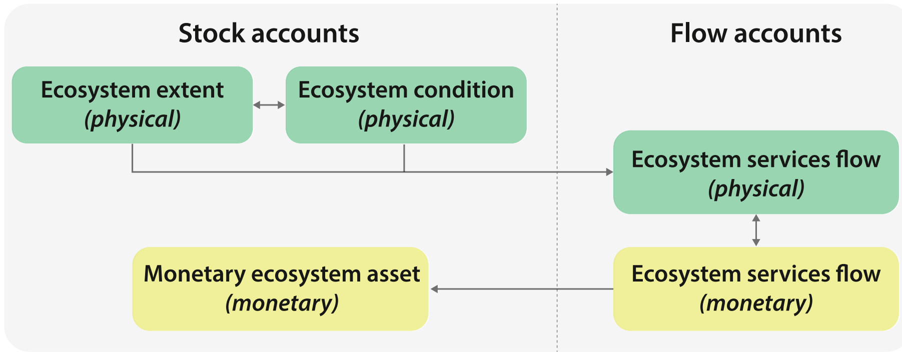

Fig. 1. The main accounts with the System of Environmental-Economic Accounting Ecosystem Accounting.

Table 1
Datasets used and investigated in this study.

Name	Source Agency	Use in this Analysis	Data Type/ Resolution	URL	Notes
Datasets used					
EPBC Act Offsets Register	DCCEEW	Identify offset and development areas	PDF Reports	https://epbcpublicportal.awe.gov.au/offsets-register/	Development plans & variations identified in reports
ACT Offsets Register	ACT Government	Identify offset and strategic assessment areas	PDF Reports	https://www.planning.act.gov.au/professionals/sustainable-development/offsets-register	
Current ACT Offset	ACT Government	Spatial data of offset boundaries	Shapefile	https://actmapi-actgov.opendata.arcgis.com	
DEA Land Cover	Geoscience Australia	Timeseries land cover 2010–2020	Raster data, 30m	https://www.dea.ga.gov.au/products/dea-land-cover	
ACT Vegetation Map (2018)	ACT Government	Extents of BGGW and NTG	Shapefile	https://www.data.act.gov.au/Environment/ACT-Vegetation-Map-2018/ykvs-cyrz/data	BGGW and NTG classes extracted
CAPAD Protected Areas	DCCEEW	Identify protected areas (IUCN Cat. IV)	Shapefile	https://www.dcceew.gov.au/environment/land/nrs/science/capad	
ACT Territory Plan	ACT Government	Land zoning data for the ACT	Shapefile	https://app2.actmapi.act.gov.au/actmapi/index.html?viewer=territoryplan	
Datasets investigated but not used					
ECNES	DCCEEW	Identify extents of BGGW and NTG	Shapefile	https://www.dcceew.gov.au/environment/environmental-information-data/databases-applications/ecnes	Assessed for comparative purposes, however likely extent of NTG in this dataset too coarse for inclusioni in the main analysis
National Vegetation Information System (NVIS)	DCCEEW (2020)	National vegetation extents in 1750, 2010 and 2020	Shapefile	https://www.dcceew.gov.au/environment/land/native-vegetation/national-vegetation-information-system	Data were not used as the national map is derived from the ACT Vegetation Map

ACT Offsets Register, while one development project (EPBC Number, 2009/4805) was recorded in the ACT Offsets Register, but not in the EPBC Offsets Register. For further detail see Supplementary Information (Table S2).

The names and locations of the biodiversity offset areas corresponding to each development project approved with the condition of offsets were identified for 12 projects. All but one of the offset areas identified (EPBC Number, 2010/5520) were for developments proposed by an agency of the ACT Government (Supplementary Information Table S1). The remaining 14 developments approved on the condition of offsets had either: (1) a location that could not be determined with certainty; or (2) an offset requirement that was only triggered under certain circumstances. While general information on offset location was included in some decisions, in some cases, shapefiles could not be created (e.g., EPBC Number, 2007/3756). Most decisions had very little location information (Supplementary Information Table S1). The results are restricted to the 12 sites where both the development and offset locations are known with certainty, along with the three 'Strategic Assessment areas' identified in the ACT Offset Register (see Section 3.1). Strategic Assessment Areas were included in the analysis and assessed as an additional category to offsets and developments.

2.2. Ecosystem information

The production of ecosystem accounts for BGGW and NTG was challenging due to a lack of timeseries data on threatened communities. Data on land zoning, land cover, and estimates of BGGW and NTG extent are available (Fig. 2) and used for account production. The Ecological Communities of National Environmental Significance (ECNES) database[11] also provides estimates of the extent of BGGW and NTG in 2022. ECNES data show most of the ACT, including urban areas, as a "likely" distribution on NTG, and NTG and BGGW extent overlap (i.e., the ECNES classification is not exclusive). ECNES is a predictive map based on pre-colonisation ecosystem distribution. Because of this, the ECNES was not used for the main analysis, although it is included in the discussion of results and Supplementary Information.

To estimate the extent of BGGW and NTG, we extracted the extent of BGGW and NTG from the 2018 ACT Vegetation Map (Fig. 2C and D) and overlaid this with land cover data (Fig. 2B). This cross-classification produced a hybrid land cover and ecosystem extent account for offset, development, and strategic assessment areas (Fig. 3). The same process was used for the ECNES data (with results in the Supplementary

[11] https://www.environment.gov.au/cgi-bin/sprat/public/sprat.pl.

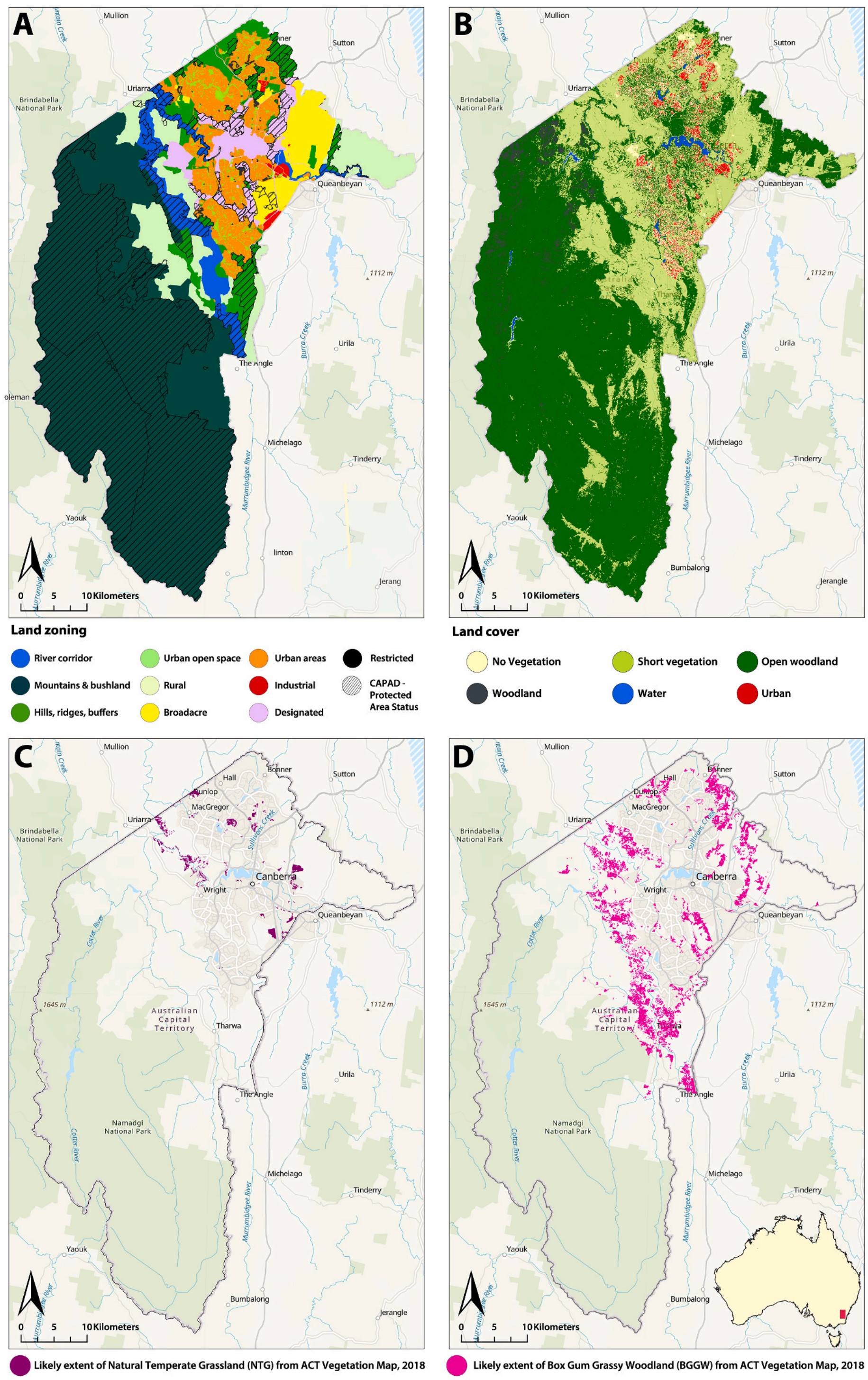

Fig. 2. Map of the Australian Capital Territory showing datasets used for the analysis. In: (A) land zoning data from ACT Territory Plan (2022) and the Collaborative Australian Protected Areas Database (CAPAD, 2022), (B) Land cover data derived from Digital Earth Australia (DEA, 2020), (C) likely distribution of NTG from the ACT Vegetation Map (ACT Government, 2018a,b), and (D) likely distribution of BGGW from the ACT Vegetation Map (2018).

Information).

2.3. Land cover information

Land cover data were used to assess changes to vegetation, bare and urban areas across the identified offset, development, and strategic assessment areas in the ACT. This was necessary because data on NTG and BGGW are only available for 2018 (see Section 2.3). Land cover information is useful for defining ecosystems (SEEA EA, paras 3.74 to 3.75), is available annually, and was used as a proxy for ecosystems in SEEA-based accounts for the ACT (Chen et al., 2023).

Land cover for the period 2010–2020 was extracted from Geoscience Australia's Digital Earth Australia (DEA) land cover product (GA, 2023). This period was selected to encompass all main development assessments and EPBC Act referrals in the ACT. The DEA data were reclassified using ArcGIS Pro to six classes: no vegetation, short vegetation, open woodland, woodland, urban, and water, and was the best match to the land cover classification of SEEA Central Framework (UN, 2014).

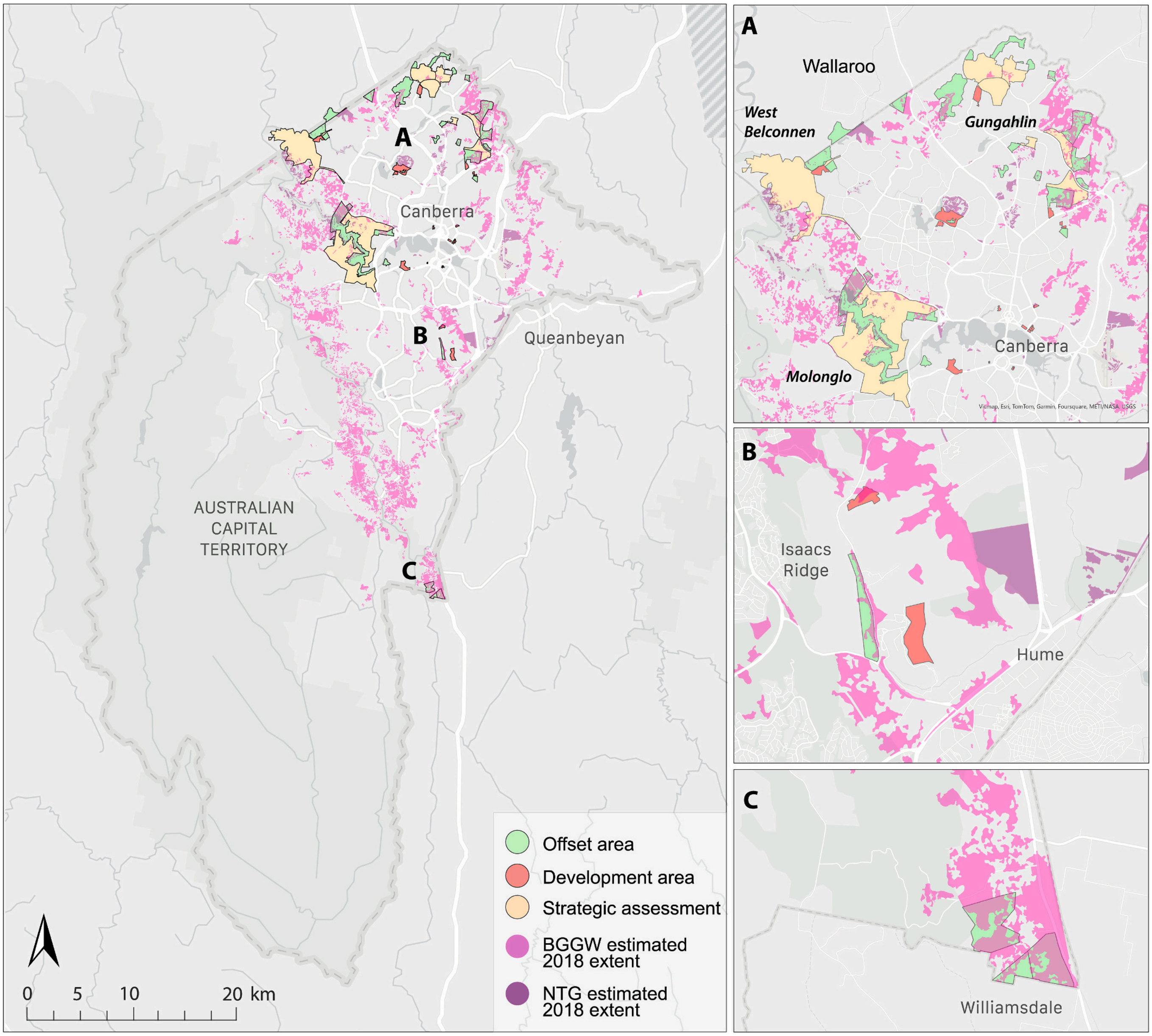

Fig. 3. Location of offset, development and Strategic Assessment areas in the ACT that were included in this study overlayed with extents of BGGW and NTG estimated by the ACT Vegetation Map (ACT Government, 2018a,b). In (A) the detail for north Canberra. In (B) the detail for central Canberra. In (C) the detail for south Canberra.

2.4. Protected areas and zoning

Protected area data for 2010 to 2020 was extracted from the Collaborative Australian Protected Areas Database (CAPAD) (DCCEEW, 2022). Land use and zoning data from the ACT Territory Plan were available for 2022, with no timeseries available. This meant that full land use accounts could not be developed. The hybrid land cover and ecosystem accounts separately identified protected areas. The zoning data (Fig. 2A) were used to identify future offset areas.

2.5. Ecosystem condition

Information on ecosystem condition was investigated with a view to producing ecosystem condition accounts. While published data is available for the ecological condition of offset and other areas (Howland et al., 2020; Carlson et al., 2021), it does not contain information on the condition of areas used for offsets when the offset was established, nor for 2010 and 2020, the reference years for the hybrid land and ecosystem asset account. As such, no ecosystem condition accounts could be produced. The data underpinning the published reports may allow the production of ecosystem condition accounts in the future (Section 4.2).

3. Results

3.1. Offsets, developments, and strategic assessment areas

Fig. 3 shows the locations of the identified offsets, development, and Strategic Assessment areas in the ACT and the capital city of Canberra. The Strategic Assessment areas are Molonglo, Gungahlin, and West Belconnen (Fig. 3A). Most (n = 9) offset sites are in north Canberra (Fig. 3A), while five are in south Canberra CBD at Isaacs Ridge (Fig. 3B) and Williamsdale (Fig. 3C) Most identified development areas (shown in red) are in central or north Canberra, the exception being the Mugga

Resources Centre (Fig. 3B).

3.2. Ecosystem accounts for offset and development areas

There is a large discrepancy between data in ECNES and the ACT Vegetation Map. In the ACT Vegetation map, the area NTG occupies 1140 ha and BGGW is 9022 ha. In ECNES, NTG is 210,365 ha and BGGW is 15,886 ha. In ECNES, all BGGW is also NTG and together these ecosystems cover 226,237 ha or 96 % of the ACT. Because the ACT Vegetation Map is based on actual, not predicted, distribution it was used as the primary data for the accounts (Table 2). Secondary accounts were produced using ECNES (Supplementary Information Table S4).

Table 2 summarises changes to NTG and BGGW stocks (ha) in development and offset areas from the 2010 Opening stock to the 2020 Closing stock. However, these data need to be interpreted with care. The ACT Vegetation Map shows the distribution of NTG and BGGW in 2018, not 2010 and 2020. Hence, the actual stock of NTG and BGGW in 2010 or 2020 is unknown. Table 2 shows that in 2020, most NTG (82 %) and BGGW (93 %) were outside the offset, development, and Strategic Assessment areas. Offsets area was 2217 ha, which is less than the 3882 ha (2.6 %) of the combined development (307 ha) and Strategic Assessment (3575 ha) areas. In 2020, the closing offset area included 147 ha of NTG and 513 ha of BGGW known to have existed in 2018, more than the area of these ecosystems affected by developments, 58 and 157 ha, respectively. In 2020, 1558 ha, or 70 % of the closing offset area was ecosystems other than NTG and BGGW.

3.3. Land cover accounts

Land cover change for offset, development, Strategic Assessment areas, and the whole of the ACT for the period 2010–2020 is shown in Fig. 4. Fig. 4A shows the vegetation composition of offset areas in the ACT. In 2020, almost all (99 %) offset areas were short vegetation (77 %) or open woodland (23 %). Woodland decreased to zero in offset areas between 2013 and 2020. Land cover in development (Fig. 4B) and Strategic Assessment (Fig. 4C) areas changed following development approval. Like offset areas, both development and Strategic Assessment areas are dominated by short vegetation (50 % and 61 % respectively), and, as would be expected, both areas have expanding areas of no vegetation and urban land cover (see Fig. 5).

Land cover data for the three Strategic Assessment areas—Molonglo, Gungahlin, and West Belconnen—are provided in Fig. 4D, E, and 4F, respectively. In these areas, 'no vegetation' and 'urban' land cover increased over time, but much short vegetation and open woodland remain.

A comparison of ACT offset to protected areas shows that offset areas have more short vegetation than protected areas (Fig. 4A and G, respectively). In 2020, protected areas were 77 % open woodland compared to 23 % in offset areas. Similarly, open woodland across the ACT (Fig. 4H) accounted for 59 % of land cover, significantly more than the 23 % for offset areas. Between 2010 and 2020, the total woodland area decreased by 5035 ha, the largest fall of any land cover, and as a percentage cover of the ACT, it fell from 4 % to 2 %. Non-vegetated and urban areas increased from 1 % to 4 % and 0.8 %–2 %, respectively.

Table 2
Ecosystem extent accounts for offset and development areas, ACT, 2010 to 2020, based on ACT Vegetation Map (ha).

	Area	Ecosystem type (ACT Vegetation Map)			*Total ACT*
		NTG	BGGW	Other ecosystems	
Opening stock 2010		**1,140**	**9,022**	**225,110**	**235,271**
Of which	Offset areas	-	91	39	*130*
	Development areas	-	-	-	-
	Strategic assessment	-	-	-	-
	Rest of ACT	1,140	8,930	225,071	*235,141*
Closing stock 2020		**1,140**	**9,022**	**225,109**	**235,271**
Of which	Offset areas	147	513	1,558	*2,217*
	Development areas	2	4	301	*307*
	Strategic assessment	56	153	3,366	*3,575*
	Rest of ACT	936	8,352	219,885	*229,172*
Net change		**(0)**	**0**	**(0)**	**0**
Of which	Offset areas	147	422	1,519	*2,087*
	Development areas	2	4	301	*307*
	Strategic assessment	56	153	3,366	*3,575*
	Rest of ACT	(204)	(579)	(5,186)	*(5,969)*

Legend: NTG is native temperate grassland, BGGW is box-gum grassy-woodland. Rows may not add due to rounding.

3.4. Hybrid land cover and threatened ecosystem accounts

Table 3 is a hybrid land cover and ecosystem extent account. It presents a cross-classification of land cover data with the distribution of NTG and BGGW according to the ACT Vegetation Map. The equivalent table using the ECNES data is in the Supplementary Information (Table S4). The table shows a decline in all vegetation classes between 2010 and 2020, with a corresponding increase in bare (no vegetation) and urban areas. In 2020, 1095 ha (93 %) of NTG and 67 % of BGGW fell within the short vegetation land cover class, and there was little change in the total area of short vegetation between 2010 and 2020 (−1 % or 771 ha). Open woodland fell by 3918 ha or 3 % between 2010 and 2020, In 2020, open woodland was associated with 2853 ha (32 %) of BGGW and 38 ha (3 %) of NTG. In the same period, woodland, the scarcest land cover in the ACT, declined from 9072 to 4037 ha (55 %) but is not associated with NTG (1 of 1178 ha) or BGGW (67 of 9022 ha).

Table 4 shows the overlap between offsets, development, and Strategic Assessment areas (land uses) with ecosystem and land cover data. It is effectively a combination of Tables 2 and 3 and is intended to help assess the changes in NTG and BGGW, for which there is only data for 2018, and the impact of offsetting using data on land cover between 2010 and 2020. This results in a 3-way classification of land cover, ecosystem type, and land use. The ecosystem-land cover classifications of interest are NTG-short vegetation, BGGW-short vegetation, and BGGW-open woodland, which in 2020 accounted for 98 % of all NTG and BGGW. The Supplementary Information, Figs. S1–S5, show the most important intersections between the 2018 ecosystem extent and 2020 land cover.

In 2020, 139 ha of NTG-short vegetation is in offset areas, 54 ha is in Strategic Assessment areas, 2 ha in development areas, and 900 ha is in the rest of the ACT (Supplementary Information Fig. S1). The developments affected 56 ha of NTG-short vegetation, and offsets for the same class were more than this by 82 ha. Outside of the offset and development areas, the NTG-short vegetation fell by 191 ha between 2010 and 2020. In this case, while there is a positive result when comparing offset to development areas, there was an overall decline in NTG-short vegetation. A similar result is found for BGGW-short vegetation and BGGW-open woodland, with offsets having more area (299 and 82 ha, respectively), than developments (Supplementary Information Fig. S2 and S3). However, between 2010 and 2020, the rest of the ACT experienced significant declines in these ecosystems-land covers: 3011 ha in BGGW-short vegetation and 5761 ha in BGGW-open woodland. The alternative account using the ECNES data is presented in the Supplementary Information (Table S4).

The decline in open woodland (3918 ha) may indicate a loss of

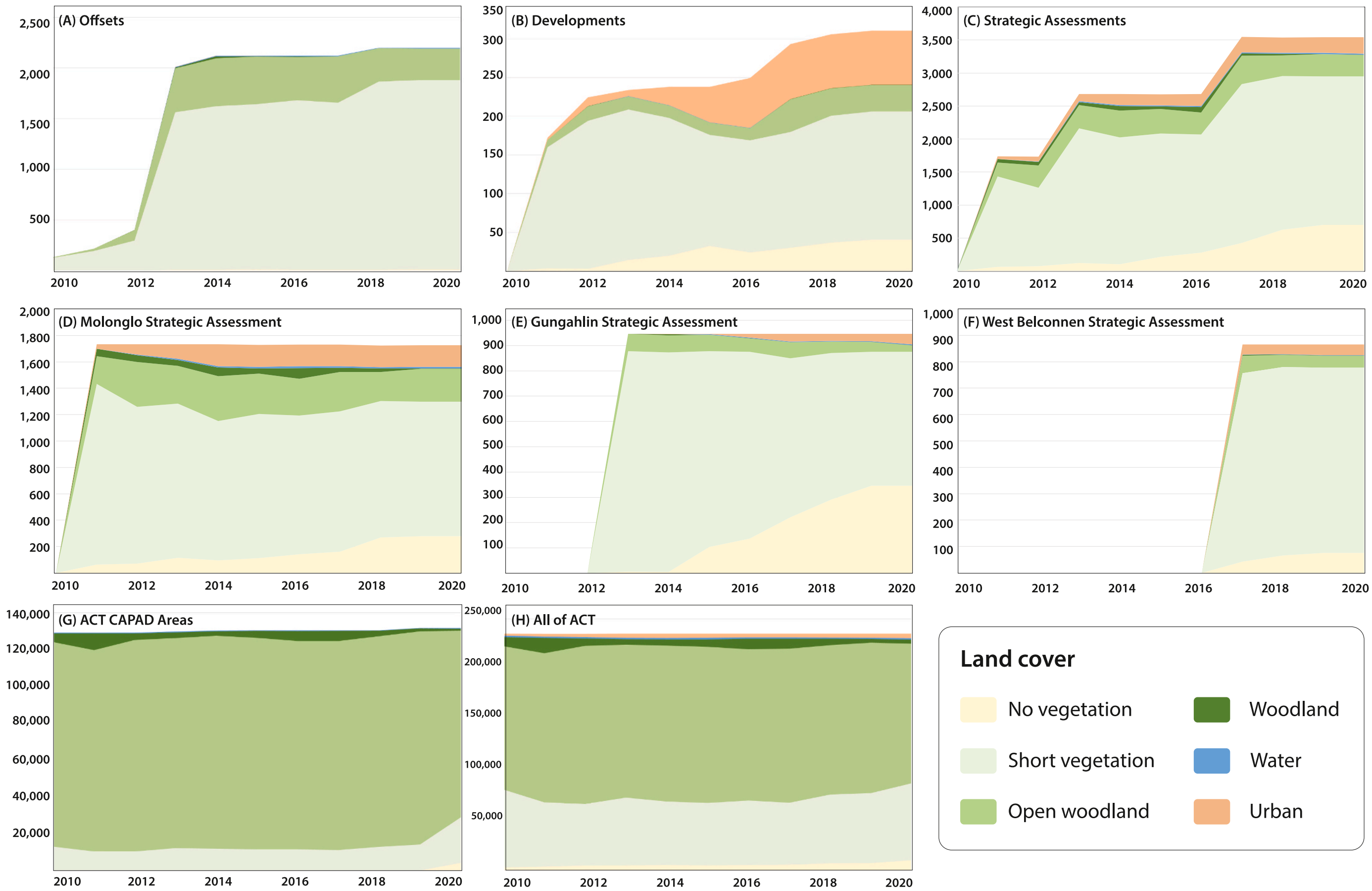

Fig. 4. Time series of land cover area (ha) in the ACT 2010–2020. In: (A) offset areas, (B) development areas, (C) Strategic Assessment areas, (D) Molonglo Strategic Assessment area, (E) Gungahlin Strategic Assessment area, (F) West Belconnen Strategic Assessment area, (G) CAPAD Status protected areas, and (H) the whole of the Territory.

BGGW after 2018, the time of the ACT Vegetation Map. This could be due to natural or human causes. The "Black Summer Fires" in January 2020 burnt 86,464 ha, impacting around 80 % of bushland (ACT Emergency Services, 2020), but there were no direct impacts to offset areas, and impacts to the BGGW and NGT extents as indicated by the ACT Vegetation Map were negligible. Changes in canopy cover due to rainfall also affects estimates of BGGW extent (Vardon et al., 2023), and some of the changes seen in Tables 3 and 4 and Fig. 4 are likely due to rainfall and fire.

3.5. Zoning of ACT biodiversity offsets

In 2020, 1454 ha of identified offset areas were within protected areas, a 1450 ha increase from 2010 (Table 5). Between 2010 and 2020, the net change of NTG conserved by offsetting outside or within protected areas was 20 ha and 127 ha, respectively. Another 97 ha was added to protected areas without offsets. Five hundred and eight (508) ha or 45 % of NTG is outside of offset or protected areas. Seventy percent (70 %) or 6303 ha of BGGW lies outside offset or protected areas, with the net change conserved by offsetting outside or within protected areas being 124 ha and 297 ha, respectively. Protected areas without offsets decreased by 10 ha because 10 ha of BGGW within protected areas in 2010 was used for offsets (Table 5; Supplementary Information Figs. S5 and S6).

Overlaying the offset and development extents with the ACT Territory Plan (a statutory spatial plan) highlights the zones used in offset implementation (Fig. 6). To date, both development and Strategic Assessment areas are in areas that have primarily urban zoning. In contrast, offset areas were mainly implemented in areas zoned as 'hills, ridges and buffers', 'river corridor', and 'rural'. No offsets or development sites were implemented in areas zoned 'mountains and bushland'.

Mapping the areas with these zoning types and removing existing offset, development, protected, and urban areas (Fig. 7), indicates the potential areas available for future offset implementation. Potential available new offset areas are in 27,239 ha of mountains and bushland, 21,485 ha of rural land, 10,186 ha of broadacre, 6726 ha of designated land, 6653 ha of hills, ridges and buffer areas, 4792 ha of river corridor, and 3610 ha of urban open space (total 80,691 ha). Many of these areas intersect with the predicted distribution of BGGW and NTG ecological communities, as shown in insets A – C of Fig. 6, and the areas of intersection are 9828 ha (available offset area and BGGW) and 77,571 ha (available offset area and NTG).

4. Discussion

The accounts and account production process shed light on many biodiversity offset policy problems and revealed opportunities for accounting to address these problems. The well-known data availability problem for offsetting policy is highlighted by account production and outlined in more detail below along with the results and how they relate to the three research questions posed in Section 1.1.

4.1. Accounts for biodiversity offset policy

Despite information deficiencies, SEEA-based accounts for the ACT were produced. The hybrid land cover, land use and ecosystem extent accounts separately identified offset and development areas, protected areas and the balance of the ACT (Tables 2–4). While accounting

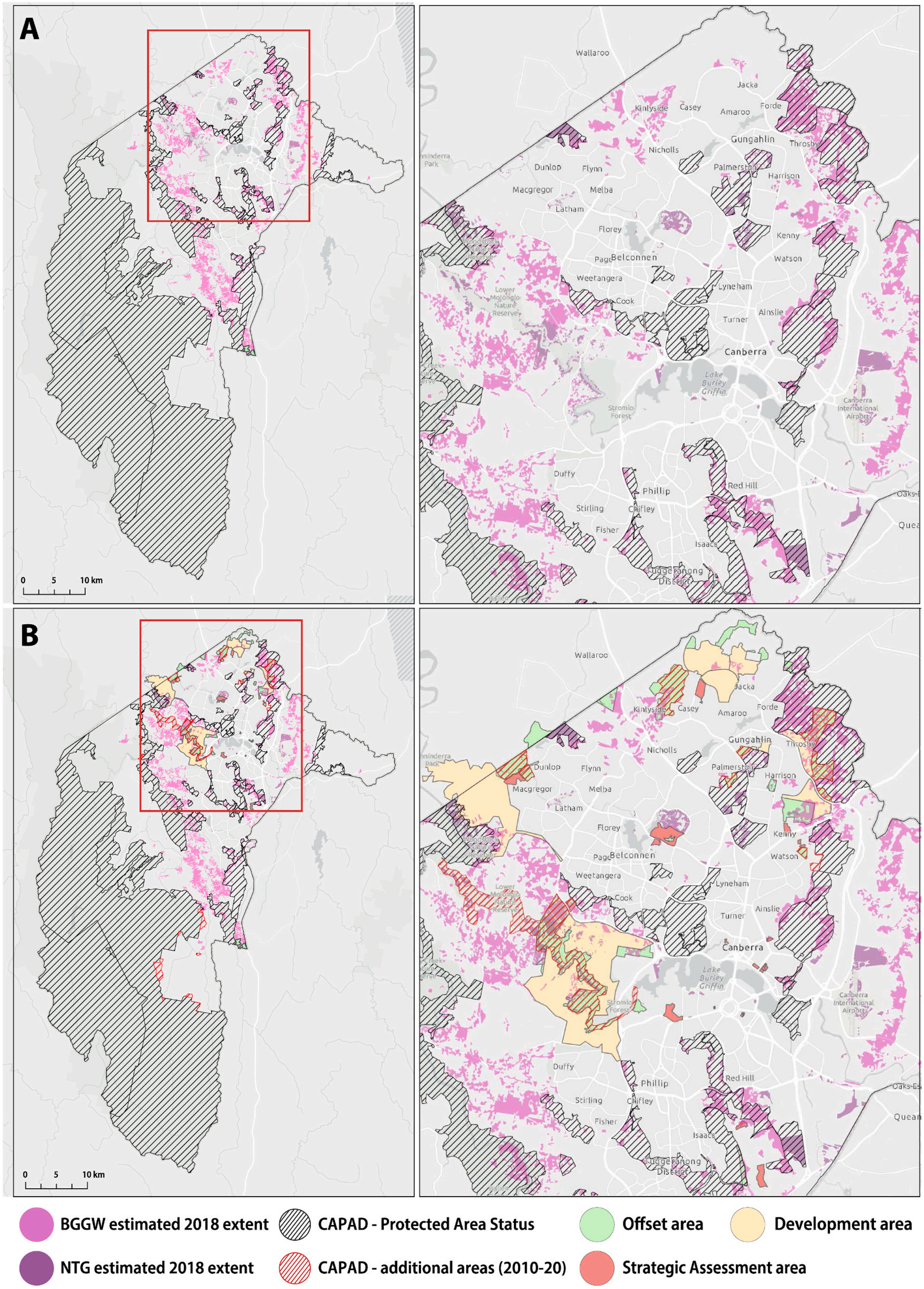

Fig. 5. Offset, development, and strategic assessment areas by CAPAD Status (IUCN Category IV). In (A): CAPAD areas designated prior to 2010 are shown (black hatch), overlaid by the estimated extents of BGGW and NTG from the ACT Vegetation Map (2018). In (B) CAPAD areas added between 2010 and 2020 (red hatch) are shown, in addition to the offset, development, and Strategic Assessment areas endorsed in the same period. Newly designated CAPAD areas overlay offset sites in Molonglo, Kenny, Casey, and Macgregor.

Table 3
Hybrid land cover and threatened ecosystem extent account, ACT, 2010 to 2020, based on ACT Vegetation Map (ha).

	Ecosystem type (ACT Vegetation Map)	Land cover						Total
		No vegetation	Short vegetation[a]	Open woodland	Woodland	Water	Urban	
Opening Stock 2010		**2,878**	**77,330**	**142,499**	**9,072**	**1,427**	**2,065**	**235,271**
Of which	NTG	-	1,091	46	3	-	-	1,140
	BGGW	3	7,136	1,787	95	-	-	9,022
	Other ecosystems	2,874	69,104	140,666	8,974	1,427	2,065	225,110
Closing Stock 2020		**10,155**	**76,559**	**138,581**	**4,037**	**1,496**	**4,443**	**235,271**
Of which	NTG	5	1,094	39	1	–	-	1,140
	BGGW	42	6,065	2,847	67	–	–	9,022
	Other ecosystems	10,108	69,399	135,694	3,969	1,496	4,443	225,109
Net Change		**7,277**	**(771)**	**(3,918)**	**(5,035)**	**69**	**2,378**	**-**
Of which	NTG	5	3	(7)	(2)	–	-	-
	BGGW	39	(1,071)	1,060	(28)	–	-	-
	Other ecosystems	7,234	295	(4,972)	(5,005)	69	2,378	-

Legend: NTG is native temperate grassland, BGGW is box-gum grassy-woodland.
[a] Short vegetation includes cropland, pastures, and native grassland. Rows may not add due to rounding.

provides an information framework, it cannot compensate for limitations in the ecological and administrative data available for account production in the ACT.

There are differences between the definitions of NTG and BGGW in the EPBC Act listing advice[12] and the ACT Vegetation Map classification (Armstrong et al., 2013; Baines et al., 2013). For example, the Act's definition for BGGW is complex and cannot be measured remotely (Vardon et al., 2023). Annual land cover data was used for account production and partly compensated for the lack of information on ecosystem extent, but the hybrid land cover and ecosystem extent accounts are open to interpretation. The situation is not ideal, and regular updates to ecosystem maps would greatly assist account production and offset policy.

The project highlighted deficiencies in administrative data within the ACT and Australian Governments. Historical land planning shapefiles were unavailable within the ACT, and information on ecosystem condition in public reports (Howland et al., 2020; Carlson et al., 2021) does not extend to when offsets were established. This was surprising as ecosystem condition is assessed at development and offset sites as part of the approval process. Information on ecosystem condition is vital as, in several cases, improvements in the condition of existing NTG or BGGW were used as offsets to compensate for the loss of these ecosystems in other areas. Further, metrics used to monitor ecosystem condition at offset sites are not the same as those used to assess ecosystem condition as part of the approval process. Such information is needed to evaluate the extent to which assumptions underpinning development approval were met or realistic, and therefore, if the methodology for offset calculation should be modified or the proponent has met their obligations.

The spatial location of 14 offset and development sites was unavailable, as were compliance reports from the Australian government's website. Government officials have advised that a website upgrade is being undertaken and will address this issue, although it's unclear if this will encompass past sites or just future ones. The inability to locate offset sites for 14 developments approved on the condition of offsets underscores data deficiencies commonly identified in assessments of biodiversity offset policies (e.g., Bull et al., 2018).

[12] https://www.dcceew.gov.au/environment/biodiversity/threatened/conservation-advices/natural-temperate-grassland-southern-tablelands.

4.2. *Insights from accounting for ACT offset policy*

Fig. 8 provides an overview of the offset policy cycle and how accounts can inform it. The objective of offsetting policy is either no net biodiversity loss or achieving a net gain after developments affecting biodiversity are identified and approved on the condition of offsets. While administrative compliance with offset policy was achieved in the ACT – the ACT Government reports annually to the Australian Government – assessing the policy objective of no net loss is challenging.

The ACT offset and development areas account (Table 2) shows more NTG and BGGW existing in 2018 were within offset areas than development or Strategic Assessment areas in 2020. However, 70 % of offset areas were ecosystems other than NTG and BGGW, and between 2010 and 2020, there was a 771 ha decline in short vegetation, 70 % of which is associated with NTG and BGGW across the ACT (Table 3). Connors (2019) observed that a greater amount of NTG was lost at development sites than gained through offsetting, while Vardon et al. (2023) found the 'likely' BGGW area in the ACT increased by 697 ha between 2001 and 2017. The 'likely' distribution of endangered ecosystems in ECNES is based on historical distribution, which is less relevant to offset policy than contemporary extent. Historical extent has been used as an ecosystem condition measure in other circumstances (Statistics South Africa, 2020).

Many development approvals were based on management actions designed to increase the condition of existing NTG and BGGW to offset ecosystem area loss. This is a trade-off between ecosystem extent and condition. While some data on ecosystem condition are available, it was unavailable for the time when offsets were established and for the period matching the ecosystem extent accounts (2010–2020); hence changes in ecosystem condition could not be determined. Apart from the establishment of the offset areas and the development of management plans, it was also impossible to assess if any changes in condition were due to natural causes (e.g. rainfall, fire, native fauna grazing) or management (e.g., weed control, fencing, tree planting) in the offset or development areas, or the whole ACT. The degree to which any positive changes to condition of existing NTG and BGGW due to management compensates for declines in ecosystem extent is a matter for judgment. It requires more comprehensive data than are currently available.

Offset areas in the ACT were likely in zones unsuitable for development (e.g., river corridors and hills, buffers and ridges). Some areas that are candidate offset sites would be expensive to establish. For example, pine forests that are zoned rural (Fig. 7B) could be converted to NTG or BGGW (2C and 2D), but this would be more costly than the restoration of former agricultural land as the pine trees would have to be removed

Table 4
Hybrid land cover, land use, and threatened ecosystems account, ACT, 2010 to 2020, based on ACT Vegetation Map (ha).

	ACT Ecosystem	Land use	Land cover						Total
			No vegetation	Short vegetation[a]	Open woodland	Woodland	Water	Urban	
Opening Stock 2010			2,878	77,330	142,499	9,072	1,427	2,605	235,271
Of which	NTG	Offset areas	-	-	-	-	-	-	-
		Development areas	-	-	-	-	-	-	-
		Strategic assessment	-	-	-	-	-	-	-
		Rest of ACT	-	1,091	47	3	-	-	**1,141**
		Subtotal	-	*1,091*	*47*	*3*	-	-	
	BGGW	Offset areas	-	86	5	-	-	-	**91**
		Development areas	-	-	-	-	-	-	-
		Strategic assessment	-	-	-	-	-	-	-
		Rest of ACT	3	7,051	1,782	95	0	1	**8,932**
		Subtotal	*3*	*7,137*	*1,787*	*95*	*0*	*1*	
	Other ecosystems	Offset areas	-	19	12	8	-	-	**39**
		Development areas	-	-	-	-	-	-	-
		Strategic assessment							
		Rest of ACT	2,875	69,084	140,654	8,966	1,427	2,064	**2,5,069**
		Subtotal	*2,875*	*69,103*	*140,666*	*8,974*	*1,427*	*2,064*	**225,108**
Closing Stock 2020			10,115	76,559	138,581	4,037	1,496	4,443	235,271
Of which	NTG	Offset areas	-	139	7	-	-	-	**146**
		Development areas	-	2	-	-	-	-	**2**
		Strategic assessment	1	54	1	-	-	-	**56**
		Rest of ACT	4	900	30	1	0	39	**974**
		Subtotal	*5*	*1,095*	*38*	*1*	*0*	*39*	***1,178***
	BGGW	Offset areas	-	415	91	6	-	-	**512**
		Development areas	-	4	-	-	-	-	**4**
		Strategic assessment	30	112	9	3	-	-	**154**
		Rest of ACT	13	5,521	2,753	58	0	6	**8,352**
		Subtotal	*43*	*6,052*	*2,853*	*67*	*0*	*6*	***9,022***
	Other ecosystems	Offset areas	5	1155	382	5	9	1	**1,557**
		Development areas	29	148	39	1	-	83	**300**
		Strategic assessment	625	2,036	376	72	19	237	**3,365**
		Rest of ACT	9,449	66,072	134,893	3,891	1,468	4,114	**219,887**
		Subtotal	*10,108*	*69,411*	*135,690*	*3,969*	*1,496*	*4,435*	***225,109***
Net change			7,277	(771)	(3,918)	(5,035)	69	2,378	-
Of which	NTG	Offset areas	-	139	7	-	-	-	146
		Development areas	-	2	-	-	-	-	2
		Strategic assessment	1	54	1	-	-	-	56
		Rest of ACT	4	(191)	(17)	(2)	0	39	(167)
		Subtotal	*5*	*4*	*(9)*	*(2)*	*0*	*39*	37
	BGGW	Offset areas	-	329	86	6	-	-	421
		Development areas	-	4	-	-	-	-	4
		Strategic assessment	30	112	9	3	-	-	154
		Rest of ACT	9	(1,529)	971	(37)	0	5	(580)
		Subtotal	*39*	*(1,084)*	*1,066*	*(28)*	*0*	*5*	(1)
	Other ecosystems	Offset areas	5	1,136	370	(3)	9	1	1,518
		Development areas	29	148	39	1	-	83	300
		Strategic assessment	625	2036	376	72	19	237	3,365
		Rest of ACT	6,574	(3,011)	(5,761)	(5,074)	41	2,050	(5,182)
		Subtotal	*7,233*	*309*	*(4,976)*	*(5,004)*	*69,*	*2,371*	1

[a] Short vegetation in includes cropland, pastures and native grasslands.

before restoration activities are undertaken. Similarly, the comparative merit and costings of retaining existing sites with biodiversity values and relocation of development sites versus site development is another matter for judgment and accounting. This requires improved data and evaluation processes and consideration of other biodiversity aspects, such as habitat connectivity and sustainability under urban expansion and climate change.

The area within the ACT suitable for new offsets is limited (Gibbons, 2011). The area in which BGGW is predicted to occur and the ACT Territory Plan land use zones where development and offsets are permitted is 9828 ha (Fig. 7). The use of offsets outside the ACT for developments within the ACT could achieve an overall acceptable biodiversity outcome (e.g., no net loss) but this would not achieve biodiversity conservation within the ACT, and ACT residents would not enjoy the broader biodiversity conservation benefits (e.g., ecosystem services).

Improvements to data collection, management and reporting are needed for ecosystem accounting to be of ongoing use in ACT biodiversity offset policy. Data availability is a common problem hindering the assessment of biodiversity offset policy (Bull et al., 2018), including the lack of public registers (Kujala et al., 2022). The EPBC Act Public Portal[13] and ACT Offset Registers are available online. Currently, the EPBC Act Public Portal cannot be searched by the species or ecological community triggering the referral to the EPBC Act, the development and offset areas cannot always be easily identified from the information provided, and compliance reports are not included.

For transparency and accountability, development approvals with a requirement of offsets should clearly define the areas (i.e., the shapefiles, cadastral parcels), the species or ecosystem triggering referral, the ecosystem condition at the time of approval, and link to the compliance reports. Where offsets are reliant on management actions to improve the

[13] https://epbcpublicportal.awe.gov.au/all-notices/.

Table 5
Protected areas and threatened ecosystems account, ACT, 2010 to 2020, based on ACT Vegetation Map (ha).

	Area	Ecosystem type (ACT Vegetation Map)			*Total ACT*
		NTG	BGGW	Other ecosystems	
Opening stock 2010		**1,141**	9,022	225,109	235,271
Of which	Offsets outside protected areas	-	90	36	*126*
	Offsets within protect areas	-	1	3	*4*
	Protected area without offsets	388	2,217	126,539	*129,145*
	Rest of ACT	752	6,713	98,531	*105,996*
Closing stock 2020		1,141	9,022	225,109	235,271
Of which	Offsets outside protected areas	20	214	530	*765*
	Offsets within protect areas	127	298	1,028	*1,454*
	Protected area without offsets	485	2,208	127,575	*130,268*
	Rest of ACT	508	6,303	95,976	*102,787*
Net change	-	-	-	-	
Of which	Offsets outside protected areas	20	124	494	638
	Offsets within protect areas	127	297	1,025	1,450
	Protected area without offsets	97	(10)	1,036	1,123
	Rest of ACT	(244)	(410)	(2,555)	(3,210)

condition of existing ecosystems, then information on management activities undertaken is needed, and the degree to which any change in condition is due to such activity is assessed and reported. Further information on how accounting could address offset policy in the ACT is found in Supplementary Information (Table S6).

4.3. *Can SEEA address common challenges with biodiversity offset policy?*

Biodiversity offset policy could potentially benefit from accounting in several ways. Accounting provides a standardised framework for organising existing information to guide offset implementation. It helps assess net biodiversity changes by distinguishing changes in ecosystem extent and condition, places offsets into ecological and socio-economic contexts through links to accounts at other spatial scales (local to national) and other account types. Use of the SEEA for offset evaluation also enables comparisons between different offset policies and programs within and between countries. It could also lead to efficiencies in the collection, consolidation and use of biodiversity data across scales. If natural capital accounting was used in the private sector, as advocated by Dickie et al. (2018), and it was SEEA-based, then public and private sector offsetting practices could be more effectively integrated and assessed.

While the ACT case study could not produce accounts that could definitively determine net biodiversity changes (e.g., no net loss or net gain), it provides insights into the barriers to account production and how accounting can aid biodiversity offset policy implementation and assessment. Accounts can be used at the beginning of the policy cycle (Fig. 8) to determine if offsetting is needed by recording the current ecosystem extent and condition and the changes over time. If developments are in endangered ecosystems, or in other ecosystems declining in area or condition, then offsets may be required. The current situation is that the need for offsets is assessed reactively, with developers and regulators assessing each development as they are submitted, and submissions are independently assessed. Accounts provide baseline data and allows proactively assessment of potential cumulative impacts. It provides information to all stakeholders (e.g., developers, regulators, and the public), which could reduce uncertainty about the need for offsets and increase confidence in offset policy.

The SEEA provides an overall conceptual framework for data on biodiversity (King et al., 2021). It defines ecosystem extent, ecosystem condition and ecosystems services, and describes their interactions. These definitions and related accounts can be used to formulate and monitor offset policy goals and to internationally standardise offset assessment. For example, the achievement of “no net loss”, “additionality” and “net gain” could be assessed based on accounts recording changes to ecosystem extent and condition. Expert judgement is needed to assess trade-offs between the loss of ecosystem extent for gains in ecosystem condition, but the accounts would provide information allowing judgement.

Accounting also makes it possible for offsets as a tool for biodiversity conservation to be seen in relation to overall biodiversity conservation. For example, no net loss for offset and development areas may be achieved, but overall biodiversity could still be in decline and recorded in ecosystem extent and condition accounts.

Accounts can be used to assess the availability of offset and development areas, as seen in the ACT hybrid land use and ecosystem extent account (e.g., Table 3) and related mapping (Fig. 7). These benefits would be greater if accounts were linked directly to spatial plans and how the plans change overtime (i.e. through updates to land use zoning). Accounts would record zoning and land use changes, (e.g. urbanisation) and their impacts on ecosystem extent, condition, and services. Such information allows stakeholders to assess past impacts of zoning and land use changes and predict the impact of future changes.

Information from ecosystem service or environmental protection activity accounts could also aid offset implementation and assess the wider changes caused through offsetting. For example, ecosystem service accounts can assess the impact of biodiversity loss on ecosystem services in development areas and the gains to ecosystem services in offset areas. This would provide a practical way to assess the “no-worse-off principle” for different stakeholders affected by no net loss biodiversity policies outlined by Griffiths et al. (2019). In this, physical ecosystem services accounts would show the changes in service flows, particularly the beneficiaries of flows, due to individual offsets and developments. A development in one area could result in ecosystem service losses to nearby residents, while offset areas may provide additional ecosystem services to residents closer to those areas. Monetary accounts for ecosystem assets and services would provide economic information relevant to land planning by, for example, identifying the areas with the cheapest potential offsets that could also deliver the greatest biodiversity gains and increases in ecosystem services. Similarly, environmental protection activity accounts from the SEEA CF (UN, 2014) could be used to determine the effectiveness of conservation management and to forecast the expected costs of ecosystem regeneration.

No attempt was made to produce ecosystem service or environmental protection activity accounts for the ACT. Many data sources and models are available that would enable some ecosystem services to be estimated (e.g., Vári et al., 2024), and some water-related ecosystem services have been estimated for the ACT (Chen and Vardon, 2024). ACT data on environmental protection *expenditure* is contained in annual budget statements,[14] but the associated environmental protection *activity* is not spatially attributed. The efficiency of offset expenditure – the

[14] https://www.treasury.act.gov.au/budget.

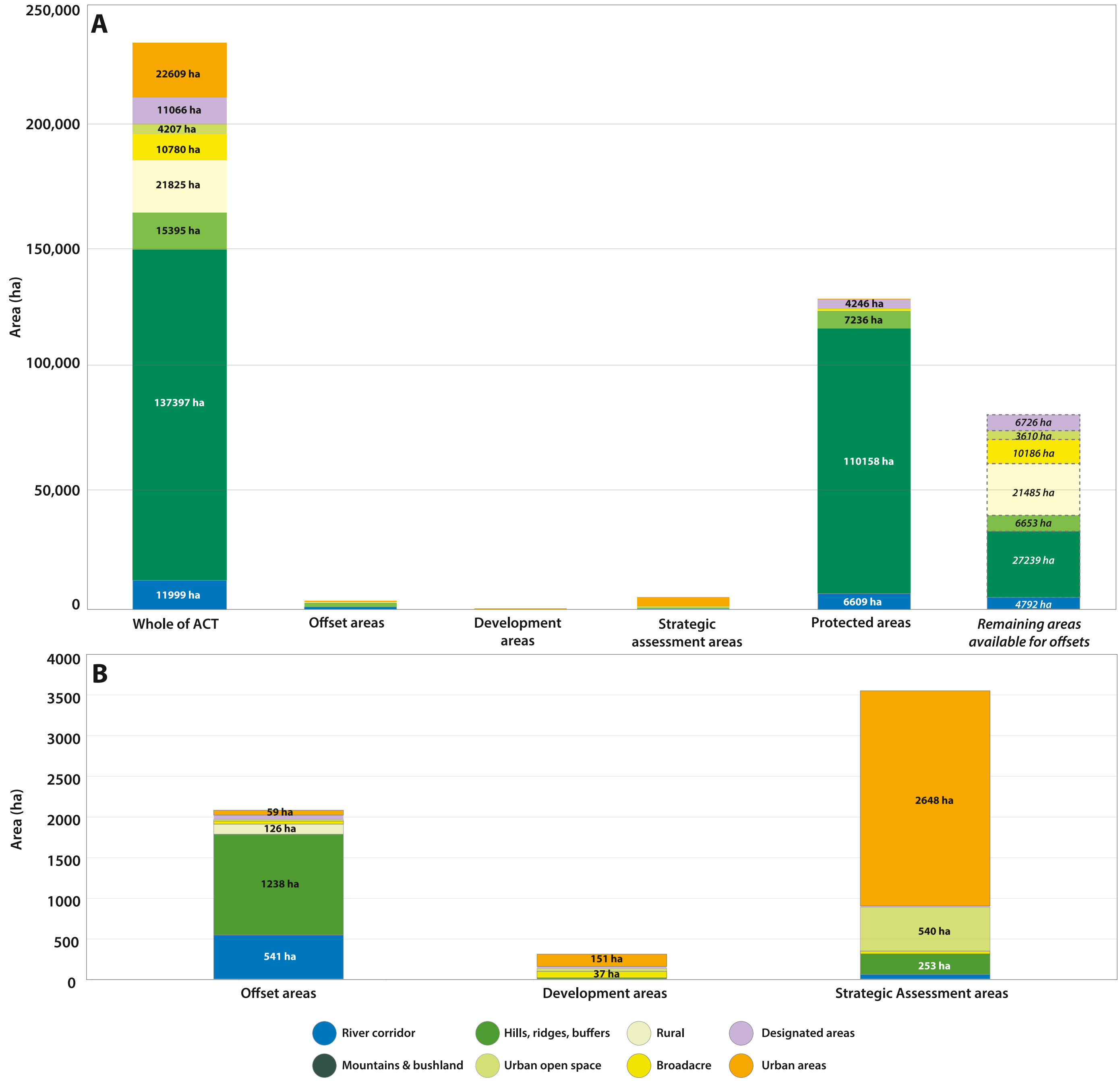

Fig. 6. Land zoning area (ha) of interest in the ACT. In (A) comparison of all areas, whole of ACT, offsets, developments, strategic assessment, and protected areas, and the remaining areas available for offsetting by land zoning. (B) provides a "zoomed" visualisation of the current zoning of offset, development, and Strategic Assessment areas identified by this study. Zoning data is derived from the ACT Territory Plan (2020).

amount of biodiversity gained per dollar spent – cannot be determined. Producing spatially referenced environmental protection activity and expenditure accounts would reveal historical costs that could be used to estimate the cost of future offsets or environmental restoration in other areas.

Compliance and enforcement of offset agreements are key issues. Accounting helps organise data and can spatially link agreements to ecosystem extent and condition. If accounts detect changes in either, this could trigger additional assessment and, where necessary, remedial action, including legal sanctions. Information from environmental expenditure accounts could be used to determine the cost of improving biodiversity to meet offset conditions.

5. Conclusion

This study aimed to assess the ability of SEEA-based ecosystem accounts to support biodiversity offset policy. To meet this aim we posed and answered three research questions. Firstly, SEEA-based accounts for biodiversity offsets were produced for the ACT despite data limitations (Tables 2–4). Secondly, while no definitive assessment of net

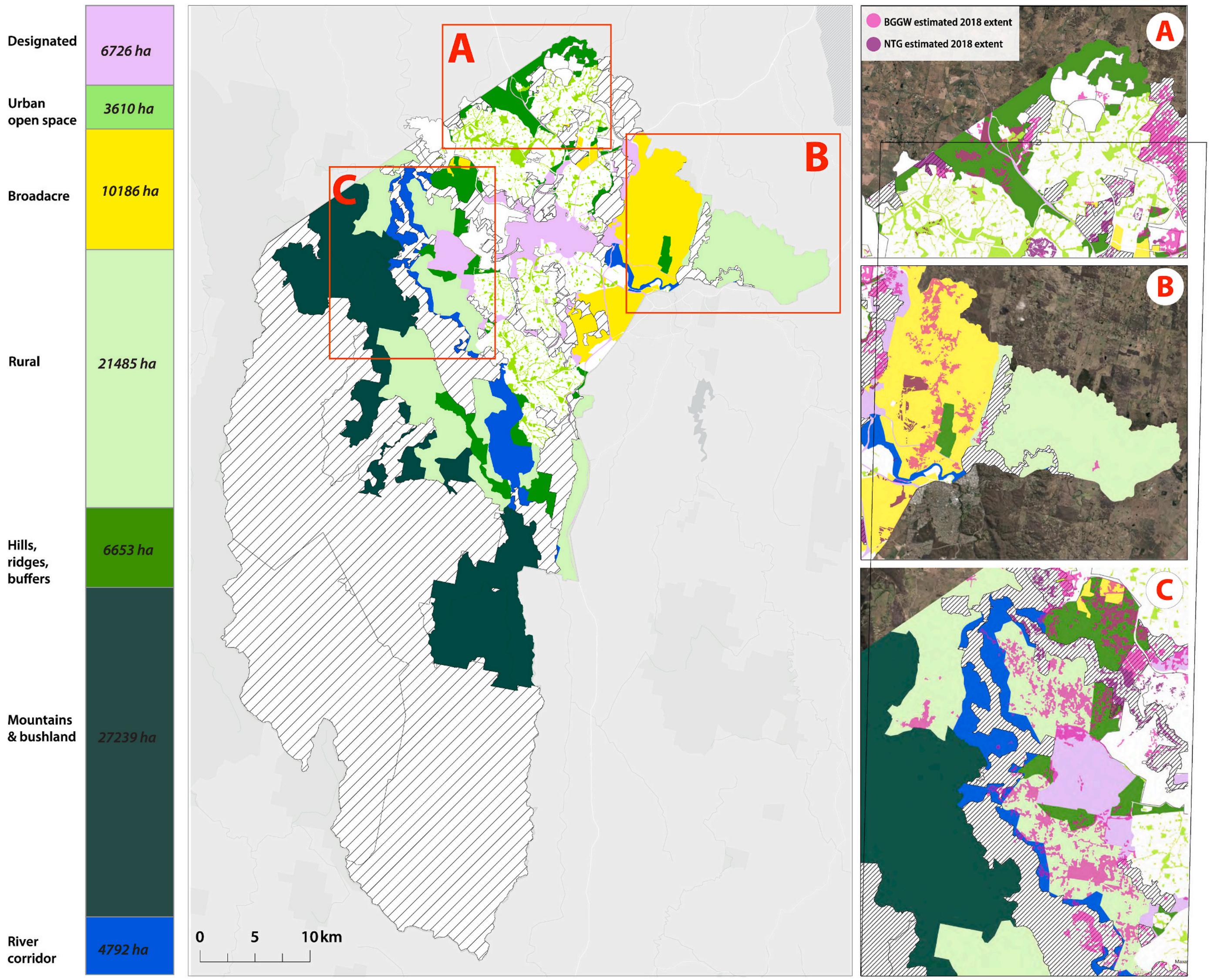

Fig. 7. Maps for future offset implementation by land zoning. Identified areas are visualised with corresponding land zoning (river corridor, mountains and bushland, hills ridges and buffers, rural, broadacre, urban open space and designated). White and hatched areas reflect areas where offsetting would not be possible due to existing urban infrastructure and offsets (white) or protected area status (hatched). Insets A - C show areas in Canberra's north (A), east (B), and west (C) with an overlay of BGGW and NTG ecological communities based on the ACT Vegetation Map (2018) in pink. These are the recommended target areas for future offset implementation based on these two biodiversity values.

biodiversity change in the ACT was possible, the accounts reveal that the area of two endangered ecosystems (NTG and BGGW) requiring offsets was greater in offset areas than in development areas. However, the overall area of the land cover types associated with these ecosystems decreased in these areas and the whole ACT, while the area available for future offsets and development in the ACT is limited. Thirdly, accounting can guide offset policy, assisting with problem identification, defining net biodiversity change in terms of ecosystem extent and condition, aid offset implementation, spatial planning, and offset monitoring, enforcement and compliance (Fig. 8). Together these would enhance the integration of offset policy across spatial scales, enable comparisons between jurisdictions with different offset policies and regulatory frameworks, and offsetting to be seen in broader environmental and socio-economic contexts by linking to other SEEA accounts.

We conclude that SEEA-based accounts could inform biodiversity offset policy by providing a standardised structure for implementing and assessing offsets. However, at present account compilation is hampered by poor data and reinforces the need for long-term biodiversity monitoring and reporting. Further research is needed to explore how additional accounts for ecosystem services and environment protection activity can assist offset policy. As part of ACT account compilation, administrative and environmental data deficiencies were identified. These can be rectified but require resourcing. Accounting is not a solution by itself, but the systematic organisation of information using accounting enables comparisons between offset policies, reveals the impact of individual development decisions requiring offsets on biodiversity, places offset policy into the broader contexts of land planning, biodiversity conservation, and losses and gains of ecosystem services.

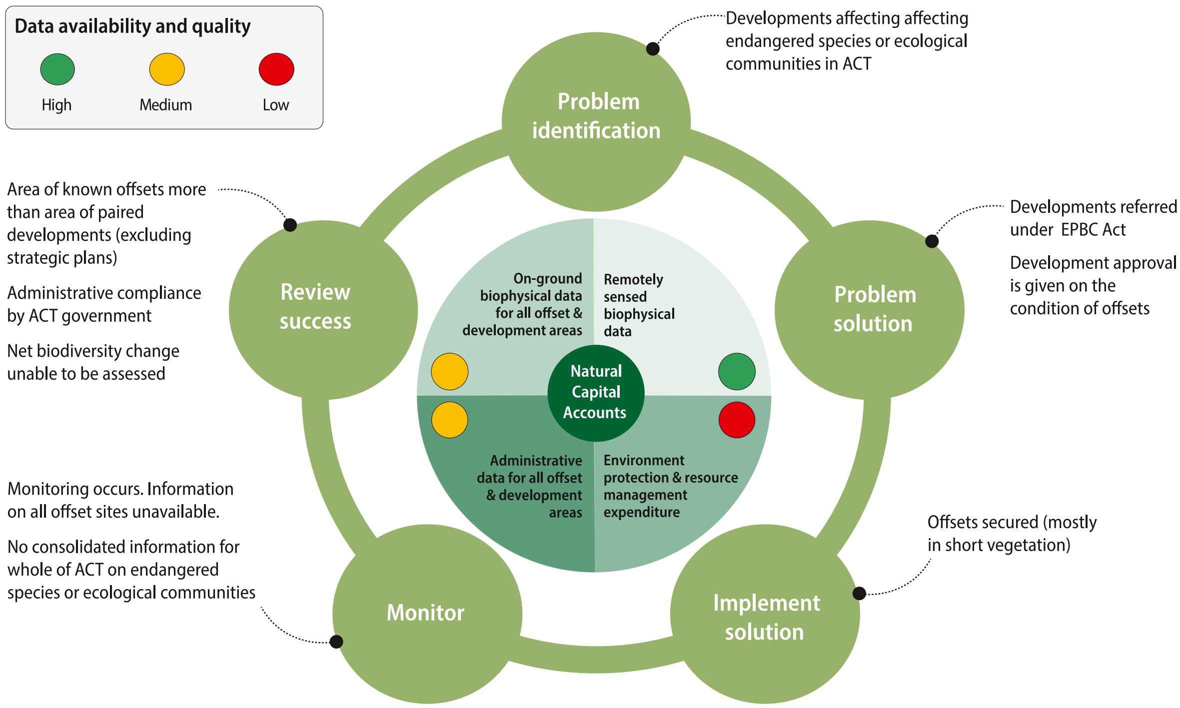

Fig. 8. The policy cycle, biodiversity offsetting and natural capital accounts.

CRediT authorship contribution statement

Michael Vardon: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Anna Normyle:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Data curation, Conceptualization. **A. Jasmyn J. Lynch:** Writing – review & editing, Supervision, Resources, Investigation, Conceptualization. **Peter Burnett:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Philip Gibbons:** Writing – review & editing, Supervision, Investigation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Michael Vardon reports a relationship with Australian Government Department of Climate Change Energy the Environment and Water that includes: consulting or advisory. Other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.indic.2025.100687.

Data availability

Data will be made available on request.

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