A Coastal Wetland Restoration First Pass Prioritisation for Blue Carbon and Co-benefits in NSW

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Cover images: Tuckean Swamp on the Richmond River has been isolated from the tide for 50 years when the Bagotville Barrage was constructed in 1971. Sources: (clockwise from top left) Evan Williams, DPI Fisheries, Crown Lands Historical Imagery.

This report provides advice for projects that could achieve addition carbon sequestration compared to the current regime of management undertaken for the subject lands. Works that are additional may be eligible to be registered with the Commonwealth under the ERF, when the blue carbon methodology has been applied.

Executive summary

Coastal wetlands dominated by mangroves and saltmarshes provide many ecosystem services including coastal protection from flood and storm events, wildlife habitat, and nutrient cycling, They also provide important social and cultural co-benefits such as enhanced recreation opportunities, job generation and revenue opportunities for stakeholders. The carbon storage, sequestration and cycling services provided by coastal wetlands is receiving considerable scientific interest as carbon storage and sequestration is amongst the highest of ecosystems globally. This occurs because saline anaerobic conditions inhibit decomposition of organic material within substrates allowing carbon to accumulate for long periods. Known collectively as blue carbon ecosystems, the carbon storage and sequestration services provided by coastal wetlands has also received government interest due to the urgent need to mitigate atmospheric carbon. If managed appropriately, blue carbon will make an important contribution towards the NSW Government's goal to reach zero net emissions by 2050, as part of the Net Zero Plan. For this to be achieved using blue carbon, carbon addition to coastal wetlands must exceed carbon losses, resulting in a net increase in carbon storage.

This project: A Coastal Wetland Restoration First Pass Prioritisation for Blue Carbon and Co-benefits in NSW was funded by the NSW Government under Initiative 2 of the Marine Estate Management Strategy 2018–2028 (MEMS): 'delivering healthy coastal habitats with sustainable use and development' (NSW Government, 2018). This output will help achieve the NSW Government's broad vision for the NSW marine estate: *A healthy coast and sea, managed for the greatest wellbeing of the community, now and into the future*. It will also inform delivery of other MEMS actions and initiatives, in particular, the development of estuary specific marine vegetation strategies and prioritisation and undertaking of on ground coastal wetland rehabilitation projects that could involve the restoration of natural hydrology.

The Commonwealth Government of Australia, through the Clean Energy Regulator, is developing a methodology for granting Australian Carbon Credit Units (ACCUs) for carbon sequestration in biomass and soils, and avoided emissions from the restoration of coastal wetlands following tidal reintroduction. Once implemented, the new blue carbon method under the Emissions Reduction Fund (ERF) will incentivise activities that reintroduce tides (e.g. removal of instream barriers, land-use planning for sea-level rise) and result in restoration and expansion of supratidal, mangrove, saltmarsh and seagrass habitats. To gain maximum benefit from this opportunity, there remains a need to identify priority areas for blue carbon restoration and management that will maximise Australia's efforts to mitigate climate change using blue carbon. A pixel-based approach was used to systematically assess blue carbon priority areas where storage, preservation, permanence and generation are high along the NSW north and south coasts. This data was assessed in the context of current land-use activities that either promote delivery of blue carbon services (such as conservation areas) or contribute to a deterioration of blue carbon (such as grazing, cropping and horticulture) to provide an indication of current blue carbon potential in NSW.

As wetland drainage and flood mitigation works that limit tidal exchange across coastal floodplains can significantly alter the capacity for generation of blue carbon, maps of blue carbon potential were investigated to identify blue carbon priority areas that were located in watersheds upstream of instream barriers. These maps, available from NSW DPI Fisheries Spatial Data Portal, identify priority areas where the opportunity cost of repair, replacement or upgrading of in-stream structures should be considered against the opportunity to significantly improve blue carbon services and other co-benefits. Co-benefits provided by coastal wetland restoration include fish passage and habitat, improved water quality, reduction in acid sulfate soils and

blackwater impacts, enhanced trophic food webs and expansion of wildlife habitat. Additionally, restoration of blue carbon ecosystems may be offset by crediting of ACCUs to projects registered under the ERF, unlike activities that repair, replace or upgrade flood mitigation structures and instream-barriers. This analysis confirmed that coastal geomorphology has a remarkable influence on blue carbon services, with significantly more blue carbon potential associated with the broad coastal floodplains of northern NSW (51.5 km^2) than the relatively narrow coastal floodplains of southern NSW. Restoration that reinstates tidal exchange to the floodplains of Clybucca River, Tuckean Broadwater, Belmore River and Wallamba River offers the greatest opportunities for enhancing blue carbon services.

Tidal reintroduction has already commenced in some watersheds of the NSW North Coast and notable examples include restoration at Hexham and Tomago Swamps on the Hunter River, Big Swamp on the Manning River and Yarrahapini Wetland on the Macleay River. These successes provide evidence supporting the reintroduction of tides as an activity for mitigating climate change within the ERF. The ERF provides considerable incentive for tidal reintroduction, and ACCUs granted to registered projects could offset some costs associated with loss of agricultural productivity and reintroduction of tides. In some locations, tidal reintroduction will occur on low-lying land, particularly where aging in-stream barriers are no longer holding back the tide, or where sea-level rise will cause tides to over-top in-stream barriers. In these circumstances, approval processes to reinstate tidal barriers should be augmented to ensure blue carbon opportunities provided by the ERF are adequately accounted for when costing the repair or re-construction of existing barriers or when establishing new instream barriers. Given the aging network of 4200 in-stream structures in NSW estuaries and anticipated acceleration in sea-level rise, it is probable that applications for upgrade or construction of new barriers will increase.

Stakeholders that may be involved in future tidal reintroduction are diverse and include Indigenous communities and native title holders, coastal landholders, private individuals, local councils, state government agencies, protected area and crown land managers. To ensure stakeholders involved in future tidal reintroduction activities benefit from the ERF there remains an urgent need for information about the location, ownership, land tenure, structure, condition and height of in-stream barriers to ensure re-connection activities are prioritised based on urgency. This information is critical because coastal wetland restoration that commences due to failure of an aging in-stream barrier, prior to ERF project registration, may be ineligible under the ERF (as it does not satisfy the ‘additionality requirement’) and the opportunity for the land manager, or broader community to benefit financially from the ERF may not be achieved. Additionally, opportunities provided by the ERF may motivate stakeholders to reinstate tidal exchange sooner and therefore, improve the capacity of land to adapt to sea-level rise prior to significant acceleration in sea-level rise. Implementation of activities in advance of substantial sea-level rise requires additional information about the projected effects of sea-level rise on tidal planes and the likelihood of instream barriers being over-topped. To fully realise these opportunities and ensure that NSW is well placed to make timely decisions, we recommend the following:

- Auditing the location and condition of constructed tidal barriers in NSW;
- Quantifying the projected effects of sea-level rise on tidal planes;
- Assessing the efficacy of existing barriers under different sea-level rise scenarios;
- Developing decision support tools for evaluating economic and environmental costs and benefits of tidal barrier decisions; and
- Establishing policy requiring site specific accounting of blue carbon and other co-benefits potential to ensure informed decision making regarding proposed upgrades of existing or construction of new tidal barriers.

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1 Introduction

Low energy intertidal environments support coastal wetlands dominated by mangroves and saltmarshes; these wetlands provide many ecosystem services, including coastal protection, wildlife habitat, nutrient cycling and carbon storage (Barbier et al., 2011; Costanza et al., 2014). Carbon storage, sequestration and cycling services provided by coastal wetlands is receiving considerable scientific interest as carbon stocks may be an order of magnitude higher than tropical rainforests and other terrestrial ecosystems (Murray et al., 2011). In particular, the saline anaerobic conditions in which coastal wetlands thrive inhibits the decomposition of organic material within substrates, and substrate volumes continue to accumulate mineral and organic material within their substrates for long periods of time (Duarte et al., 2005; McLeod et al., 2011; Duarte et al., 2013). Known collectively as blue carbon, the carbon storage and sequestration services provided by coastal wetlands has also received government interest due to the urgent need to mitigate atmospheric carbon (Kelleway et al., 2017b; Kelleway et al., 2020). For this to be achieved using blue carbon, carbon addition to coastal wetlands must exceed carbon losses, resulting in a net increase in carbon stocks.

Globally there has been significant deceleration in the loss of coastal wetlands by conversion to other land uses, such as shrimp aquaculture, coastal developments, forestry and palm oil plantations (Friess et al., 2019; Friess et al., 2020). In Australia there has been policy implementation at national and state levels that has halted the decline in coastal wetland extent (Rogers et al., 2016). Whilst these efforts to protect and conserve coastal wetlands has arrested carbon emissions resulting from the conversion of coastal wetlands, and have been effective in maintaining carbon services, they do little to increase carbon drawdown and contribute to climate mitigation efforts.

Some carbon additionality occurs as coastal wetland vegetation grows and adds biomass, or through the accumulation of mineral and organic material within substrates. However, this additionality is relatively minor and may be offset by natural processes of organic matter decomposition. Effectively harnessing the carbon services provided by coastal wetlands to achieve carbon additionality requires an increase in the three dimensional space occupied by coastal wetlands (Rogers et al., 2019a). As they occur at the interface between the land and the sea, an increase in lateral extent can be facilitated by increasing the area of tidal inundation, or by facilitating the vertical growth of substrates and sequestration of organic material. Fortunately, there remains considerable capacity for additionality to be achieved now and in the future (Rogers et al., 2019b).

As coastal wetlands occupy low-lying, often highly fertile land, they have a history of conversion to other land use and have been impacted by encroaching urbanisation, industrial developments and agriculture (Rogers et al., 2016). This is particularly the case in eastern Australia where large scale programs to drain coastal wetlands and facilitate conversion to other land uses occurred between the 1900s and 1980s (Goodrick, 1970; Saintilan and Williams, 2000; Sinclair and Boon, 2012; Creighton et al., 2015), ceasing only when effective legislation inhibiting loss of coastal wetlands was enacted (Rogers et al., 2016). These programs of drainage, often under the guise of flood mitigation works, resulted in engineered structures being established to facilitate drainage (e.g. ditches, dykes, ring drains) and impede tidal exchange (e.g. floodgates, barrages, culverts, bunds, levees) (Tulau, 2011). The outcome of these activities has been increasing coastal wetland clearance, agriculture and urbanisation on coastal floodplains. In NSW alone, 4200 structures are estimated to impede flows in coastal rivers and streams (Williams and Watford, 1997). The drainage of freshwater wetlands on the floodplain and exclusion of tidal exchange has changed wetland hydro-period. This has facilitated the conversion of saline wetlands on land behind these structures into freshwater wetlands or pasture suitable for grazing and cropping. Inundation regimes have reduced from 100 + days to generally < 10 days enabling establishment of introduced pasture grasses to facilitate their conversion to fully agricultural landscapes (Tulau, 2011). Rogers et al. (2015) calculated the loss of potential fish habitat (including mangrove and salt marsh) by drainage in the same region assessed by (Goodrick, 1970), finding that 62,258 ha were drained since European settlement, constituting over 70% of the pre-European extent of 87,008 ha.

Implementation of wetland drainage and flood mitigation works has not come without ‘side effects’. Some of the land that is now cut-off from tidal exchange may have converted from being carbon sinks into likely sources of methane emissions (Poffenbarger et al., 2011). This is particularly concerning given the 25-100 times greater radiative forcing of atmospheric methane than carbon dioxide (Kroeger et al., 2017). Additionally, exposure of potential acid sulfate soils to aerobic conditions has activated the generation of acid sulfate soils, acid run-off and a suite of ecological impacts (Sammut et al., 1995; Sammut et al., 1996), whilst eutrophication may begin to dominate (Lovelock et al., 2009). The resulting rapid loss of organic material within substrates, that will likely have increased methane and carbon dioxide emissions, has also contributed to loss of substrate volume and elevation (Belperio, 1993), with the outcome being that once profitable agricultural land becomes increasingly less viable for grazing and agricultural purposes. In some situations this has increased exposure of peat substrates to fire, which can cause significant slumping of ground surfaces. Indeed, peat fires near Port Macquarie were reported to have burnt for 210 days before being put out by a significant rainfall event in 2020 (Wellauer and Rubbo, 2020). In many places, the benefits of wetland drainage works are no longer being realised, and efforts are now being put in place to restore prior coastal wetlands by managing floodgates and reinstating tidal exchange. For example, restoration activities have occurred at Yarrahapinni Wetland on the Macleay, restoring over 700 ha of drained estuarine wetland; whilst over 200 ha of drained freshwater and brackish wetland at Big Swamp on the Manning River has undergone tidal reinstatement (Rogers et al., 2015). In some cases, restoration of tidal exchange has been facilitated by the failure of engineered structures (Dwyer *pers. comm.*) – it is evidently difficult to hold back the sea indefinitely. Elsewhere, the benefits will likely become increasingly limited as sea-level rise will increase the elevation of tidal planes, and existing engineered structures may not effectively impede tidal exchange in the future (Hanslow et al., 2018; Hague et al., 2020).

The reality of aging engineered structures, many of which are deteriorating or no longer meeting design expectations of holding back the tide, may provide an opportunity for blue carbon additionality. Areas once cut-off from tidal exchange will offer the much-needed space for blue carbon ecosystems to expand and increase carbon sequestration and storage; and if the space is not suitable for tidal exchange and coastal wetland restoration now, it may well be once anticipated sea-level rise is realised. Furthermore, the societal and political appetite for blue carbon contributing to climate mitigation efforts is becoming favourable with numerous schemes either in development or already in place that would provide a payment for carbon ecosystem services. Indeed, for some very low-lying coastal floodplains blue carbon restoration opportunities may become the most viable land-use option as sea-level rise continues. In Australia, there is a burgeoning voluntary carbon off-setting market, and the Commonwealth Government has stated its intentions to use blue carbon as a mechanism that contributes to Australia's climate mitigation efforts (Australian Government Clean Energy Regulator, 2016). Administered by the Commonwealth Government Clean Energy Regulator, the Emissions Reduction Fund could provide a payment for blue carbon additionality, providing it can be adequately verified. Efforts are underway to develop a methodology for quantifying blue carbon resulting from activities that promote carbon additionality, such as removing barriers to tidal exchange and planning for sea-level rise retreat pathways (Kelleway et al., 2020; Clean Energy Regulator, 2021).

Prioritising areas suitable for coastal wetland restoration remains a critical knowledge gap. Rogers et al. (2019b) developed a spatial framework for assessing blue carbon stocks and additionality that relied on relatively accessible spatial datasets that were analysed using an indicator-based approach. Recognising geomorphological control on the distribution of blue carbon ecosystems and the preservation of sequestered carbon, the broad-scale approach included a first pass assessment of the capacity for blue carbon storage, preservation, generation and permanency within coastal landscapes. This prioritisation was moderated based on whether current land-use activities were compatible with the blue carbon services being provided; however, it did not explicitly consider the role of wetland drainage and flood mitigation activities in moderating blue carbon services.

In this study, we apply the blue carbon spatial framework with the intent of identifying the floodplain areas impacted by wetland drainage and flood mitigation works because they could be used to prioritise coastal wetland restoration activities. We anticipate that application of this framework to prioritise areas for coastal wetland restoration will provide additional confidence when considering sites and activities to meet blue carbon objectives of climate mitigation. This framework is applied to the north and south coasts of New South Wales, and excludes the metropolitan region of Sydney (i.e. south of Tuggerah Lake to north of Lake Illawarra) where the sub-surface mapping of the coastal Quaternary geology is less reliable due to the lack of field validation to resolve uncertainty in areas where anthropogenic reworking of surface veneer sediments had occurred (Troedson and Deyssing, 2015). In doing so, the analysis excludes the tide-dominated drowned river valley estuaries that dominate the Sydney Metropolitan area, although some large embayments remain within the analysis such as Batemans Bay and Jervis Bay. The spatial framework is defined based on geomorphological control of blue carbon, and applying the framework to the north and south coasts NSW provides the opportunity to consider the implications of wetland drainage and flood mitigation activities on the predominantly wave-dominated estuaries that occur along these coasts.

1.1 Mitigating climate change using blue carbon

Blue carbon ecosystems, particularly those dominated by mangroves and saltmarshes, are particularly efficient at storing carbon (Figure 1) (Duarte et al., 2005; McLeod et al., 2011; Duarte et al., 2013; Macreadie et al., 2017b). However, unlike terrestrial ecosystems that were well-known carbon sinks, much of the blue carbon stored within coastal ecosystems is sequestered in substrates. This soil organic material becomes concentrated for multiple reasons: i) tidal inundation creates anaerobic conditions that slows decomposition (McLeod et al., 2011); ii) tidal inundation by saline waters slows methanogenic decomposition (Poffenbarger et al., 2011); and iii) organic matter accumulation and carbon sequestration continues as vertical space for carbon storage does not become fully occupied by mineral sediments (see for example McKee, 2011; Adame et al., 2021). This latter mechanism can be enhanced when seas are rising at rates that promote organic matter addition within substrates (Rogers et al., 2019a). Additionally, providing a natural hydrological regime is maintained, sequestered carbon is buffered from loss back into the atmosphere that can arise from bush fires. As an outcome of high carbon storage, there is increasing interest in quantifying carbon storage and leveraging carbon storage to reduce atmospheric carbon concentrations.

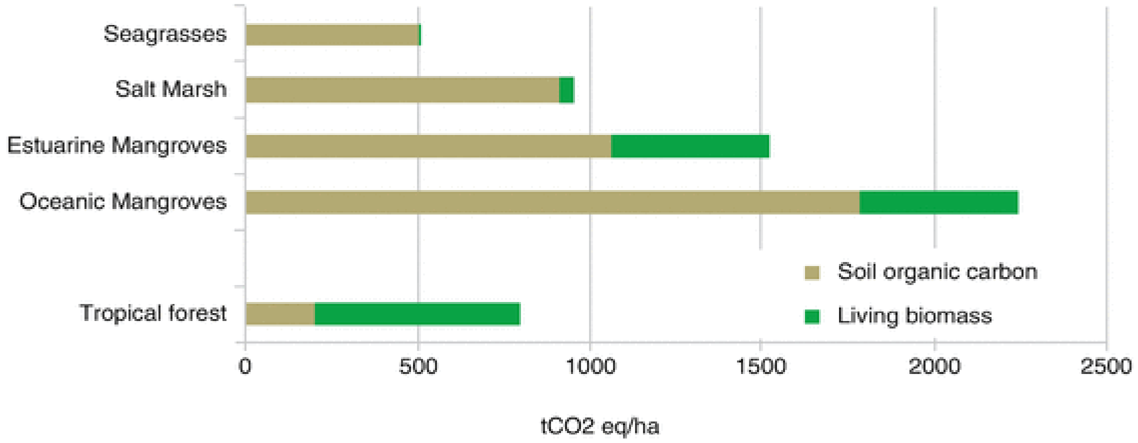


Figure 1: Global averages for soil organic carbon and living biomass for mangroves, saltmarshes and seagrasses. Mangroves and saltmarshes store considerably more carbon within living biomass and substrates than tropical forests, which are more commonly regarded to be carbon rich. Source: Murray et al. (2011).

The Kyoto Protocol, which was adopted in 1997 and enforced in 2005, operationalises the United Nations Framework Convention on Climate Change (UNFCCC). By endorsing the protocol, industrialised countries and economies in transition committed to limit and reduce greenhouse gas emission according to nationally determined targets. This initiated a process of developing methodologies for estimating national inventories of anthropogenic emissions by sources and removals by sinks; and resulted in the 2006 Guidelines for National Greenhouse Gas Inventories in 2006 (Eggleston et al., 2006). A supplement to these guidelines was developed in 2013 (Hiraishi et al., 2014), and was later refined in 2019 that focussed on methodologies for determining national greenhouse gas inventories from wetlands (Buendia et al., 2019). These methodologies provided the framework for accounting for carbon storage by blue carbon ecosystems. They also confirmed that blue carbon could feasibly be traded in a carbon market.

To facilitate this process of limiting and reducing greenhouse gas emissions, the UNFCCC implemented a number of mechanisms that are relevant to blue carbon ecosystems. Reducing emissions from deforestation and forest degradation (REDD+) and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries, initially negotiated in 2005, has a primary objective of mitigating climate change through reducing emissions of greenhouse gases by managing forests in developing countries (Anglesen, 2009). The clean development mechanism, also negotiated in 2005, promotes clean development in developing countries (Sutter and Parreño, 2007). This is achieved by allowing emission reduction projects in developing countries that contribute to their own sustainable development objectives. These projects then earn certified emission reduction (CER) credits that industrialised countries use to meet part of their emission targets under the Kyoto Protocol. Notably, these mechanisms focus on activities in developing countries.

The Australian Government reports progress towards meeting national determined targets as part of its national obligations to the Kyoto Protocol, and is one of the few countries voluntarily reporting emissions and sequestration associated with blue carbon ecosystems (Australian Government Department of the Environment and Energy, 2019). Through a participatory workshop approach, anthropogenic activities that have the potential to enhance carbon sequestration or reduce/avoid greenhouse gas emissions from blue carbon ecosystems was established, and subsequently assessed. In 2017, the Australian Government identified likely carbon sequestration opportunities that blue carbon ecosystems may provide (Kelleway et al., 2017b). Recommended activities that may enhance carbon sequestration or reduce/avoid greenhouse gas emissions from blue carbon ecosystems include:

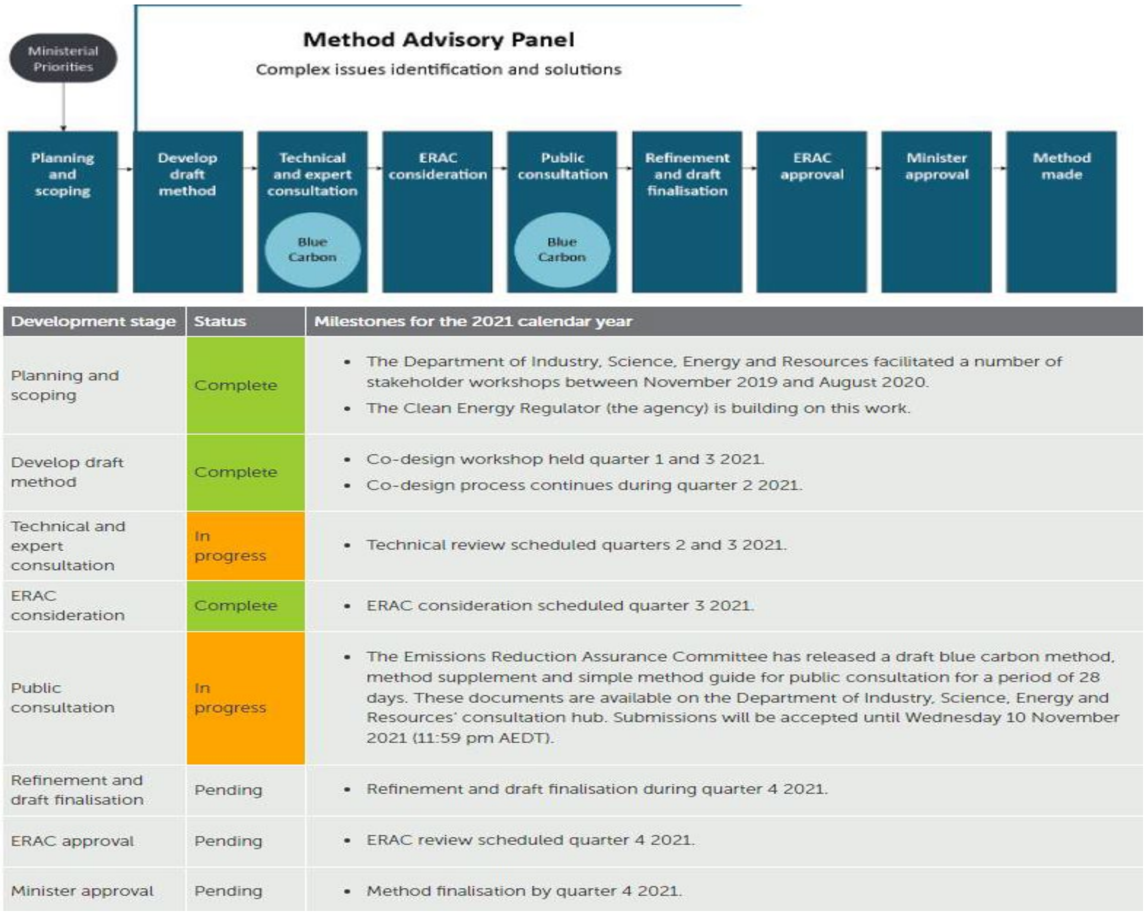
i) the reintroduction of tidal flow to mangroves and tidal marshes;
ii) avoiding clearance of mangroves and avoided soil disturbance of mangroves and saltmarshes;
iii) land-use planning for sea-level rise;
iv) avoidance of seagrass loss and re-establishment or creation of new seagrass ecosystems; and
v) avoidance of seagrass loss through direct physical disturbance.

The Emissions Reduction Fund (ERF), administered by the Australian Government Clean Energy Regulator, is a voluntary scheme that provides incentives to organisations and individuals to implement activities and technologies that reduce carbon emissions and increase carbon storage (Australian Government Clean Energy Regulator, 2016). Under the ERF registered projects are granted Australian Carbon Credit Units (ACCUs) for carbon sequestered or emissions avoided, depending on the method. The ACCUs can then be sold to the Commonwealth Government through a reverse auction process, or to anyone wishing to purchase ACCUs. Projects registered under the ERF must follow the requirements of the methodology they have registered under, and there are currently eight methods available for implementation under the ERF. The reintroduction of tidal flows to achieve the restoration of coastal wetlands has been identified as one of five additional priorities for new method development. The Clean Energy Regulator has been engaging with industry, potential end-users, technical experts and the Emissions Reduction Assurance Committee (ERAC) in a process of co-design. This process is informing method development and it is anticipated that ERAC and ministerial approval will follow (Figure 2). Future implementation of these five recommended activities as methods under the ERF will provide considerable opportunities to offset opportunity costs associated with restoration of coastal wetlands, and planning for the landward retreat of coastal wetlands with sea-level rise.

Parallel to the efforts of the Australian government, there is a growing voluntary carbon market that supports projects that enhance carbon storage or reduce greenhouse gas emissions. These markets are appealing to individuals and corporations aiming to neutralise or offset their carbon emissions. These voluntary markets operate in a similar manner to projects within the ERF, with project proponents following a verified methodology to achieve a carbon mitigation benefit. Currently the Verified Carbon Standard (Needelman et al., 2018) and American Carbon Registry offer methodologies focussed on blue carbon ecosystems (Sapkota and White, 2020).

If managed appropriately, ERF projects will make an important contribution towards the NSW Governments goal to reach net zero emissions by 2050, as indicated in the Net Zero

Plan (DPIE, 2020). This will require consideration of international obligations under the Ramsar Convention on Wetlands to maintain the ecological character of wetlands. Importantly, resolution XIII.14 attests to the role of the Ramsar Convention in meeting UNFCCC objectives, and explicitly promotes conservation, restoration and sustainable management of coastal blue carbon ecosystems; and promotes prioritisation of blue carbon ecosystems, and development and implementation of plans for conservation, restoration and sustainable management.



Development stage	Status	Milestones for the 2021 calendar year
Planning and scoping	Complete	• The Department of Industry, Science, Energy and Resources facilitated a number of stakeholder workshops between November 2019 and August 2020. • The Clean Energy Regulator (the agency) is building on this work.
Develop draft method	Complete	• Co-design workshop held quarter 1 and 3 2021. • Co-design process continues during quarter 2 2021.
Technical and expert consultation	In progress	• Technical review scheduled quarters 2 and 3 2021.
ERAC consideration	Complete	• ERAC consideration scheduled quarter 3 2021.
Public consultation	In progress	• The Emissions Reduction Assurance Committee has released a draft blue carbon method, method supplement and simple method guide for public consultation for a period of 28 days. These documents are available on the Department of Industry, Science, Energy and Resources' consultation hub. Submissions will be accepted until Wednesday 10 November 2021 (11:59 pm AEDT).
Refinement and draft finalisation	Pending	• Refinement and draft finalisation during quarter 4 2021.
ERAC approval	Pending	• ERAC review scheduled quarter 4 2021.
Minister approval	Pending	• Method finalisation by quarter 4 2021.

Figure 2: Progress towards development of a blue carbon methodology within the Emissions Reduction Fund. Source: Clean Energy Regulator (2021).

Implementation of ERF projects or similar voluntary projects requires considerable scoping to identify suitable locations for project implementation. As projects under the ERF and other voluntary schemes require an activity be undertaken, prioritisation should account for the types of activities that can be implemented. In the case of the ERF, existing methods that grant ACCUs for carbon sequestration by native ecosystems include activities that prevent the loss or disturbance of regenerating native ecosystems. In NSW there are a range of policy and legal instruments available that address loss of blue carbon ecosystems (Rogers et al., 2016), such as the *Fisheries Management Act* (1994), *Environmental Planning and Assessment Act* (1979), *Marine Estate Management Act* (2014) and *Biodiversity Conservation Act (2016)*. Implemented projects under the ERF are therefore likely to focus on activities that restore coastal wetlands through reintroduction of tidal flows or enhance adaptation of coastal wetlands to sea-level rise by planning for their landward retreat. It is anticipated that this study serves as a preliminary scoping exercise to identify locations where restoration of coastal wetlands through reintroduction of tidal flows may be achieved by managing barriers to tidal flow.

1.2 Study Location: Wave-dominated coastline of NSW

This study focuses on the predominantly wave-dominated estuaries that occur on the NSW north coast, extending from the catchment of the Hunter River to the northern border of NSW, and the NSW south coast, extending from the catchment of Lake Illawarra to the southern border of NSW (Figure 3). As sea level rose since the last glacial maximum, coastal embayments were drowned and coastal barriers that formed along the wave-dominated coast restricted tidal exchange between fluvial and oceanic water, resulting in the formation of wave-dominated estuaries. Sea level stabilised up to 1 m higher than present levels approximately 7000 years ago, before falling to present levels over the past few millennia. This period of relative stability created conditions suitable for the delivery of marine and terrigenous sediments to estuaries, resulting in progressive infill. The rate of supply and geological control of bedrock valleys has an overwhelming influence on the shape of the NSW coastline, estuaries and coastal floodplains.

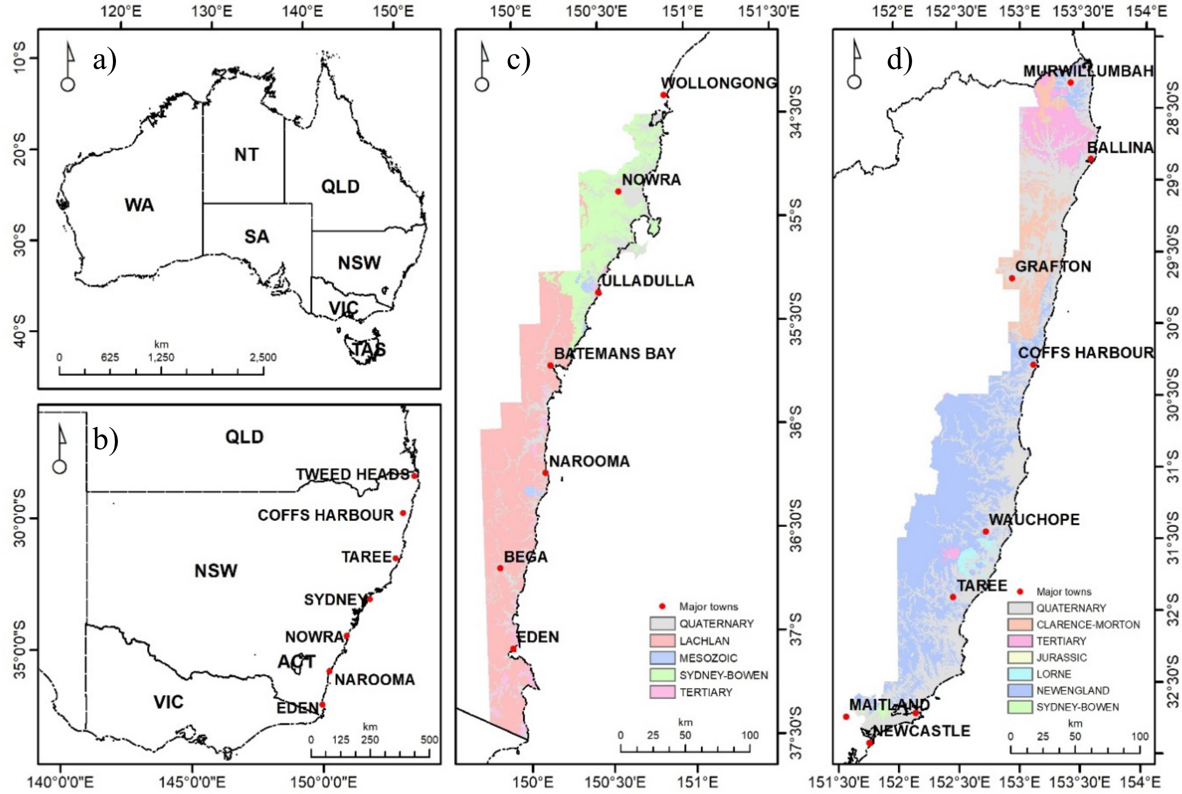


Figure 3: Location map of a-b) New South Wales, with bedrock, tertiary and quaternary geology of the c) southeastern and d) northeastern coast, indicating the spatial extent of available datasets. Source: Troedson et al. (2004)

1.3 Geomorphology as a control on blue carbon in wave-dominated estuaries of NSW

Coastal blue carbon ecosystems occur within the intertidal zone of low-energy shorelines, and are usually positioned above mean tide level. Along the wave-dominated coastline of NSW, Australia, suitable conditions are typically restricted to estuaries where entrances provide a buffer from the high-energy waves of the open coast. Roy et al. (2001) classified estuary structure for southeastern Australia based on being i) wave or tide-dominated, and ii) the degree of infill with sediment that has occurred since their formation, known as estuary maturity. This geological classification recognises that the coastal zone was located on the continental shelf during glacial periods, and coastal valleys drowned during interglacial periods (Figure 4a). Near the end of the last marine transgression when sea-level rise decelerated and stabilised (i.e. ~7000 years ago) (Lewis et al., 2013), coastal barriers along the high energy coastline enclosed many of the relatively shallow drowned river valleys creating estuaries (Figure 4b) (Roy, 1984; Sloss et al., 2005; Sloss et al., 2009) and most of the estuaries of southeastern Australia are classified as wave-dominated. Only the deepest drowned river valleys, located in the Sydney metropolitan area and Batemans Bay, are regarded to be tide-dominated (Roy et al., 2001). Since the early Holocene, estuaries have been infilling with both terrigenous sediments delivered from the catchments of rivers and streams that enter estuaries, and marine sediment delivered by tides through estuary entrances. Variation in the rate of supply of sediment to estuaries, and the size of estuaries means that estuaries can range in the degree of infill from immature stages consisting of a large waterbody (e.g. lake) and narrow coastal and alluvial floodplains, to mature estuaries that have channels traversing broad coastal floodplains (Roy et al., 2001). Estuary structure (type and maturity), waterbody size and catchment area have a profound influence on coastal blue carbon.

In the early stages of wave-dominated estuary evolution (i.e. immature estuaries), streams deliver terrigenous sediment from catchments to the open waters of estuaries and tides deliver marine sediment through estuary entrances (Figure 4c). As hydrological energy diminishes when streams enter open waters, sediment falls from entrainment and fluvial deltas form; similarly, entrained marine sediments delivered through estuary entrances on tides also accumulate where hydrodynamic energy diminishes and contribute to the development of a flood-tide delta (Roy, 1984; Roy et al., 2001). Three broad depositional environments may establish; coastal barrier, estuarine plain and alluvial plain. Fluvial and flood –tide deltas, and back barrier substrates provide favourable intertidal conditions for coastal wetland vegetation to establish and thrive; seagrass vegetation dominates subtidal regions where hydrodynamic energy is favourable. The intertidal zone within immature estuaries and the vertical distribution of coastal wetland vegetation is controlled by the influence of estuary entrance morphology on the tidal prism; constriction of the tidal prism typically results in tidal range being diminished as tides propagate into open waters of estuaries.

As an estuary infills with sediments, fluvial deltas and flood-tide deltas encroach upon open estuarine waters; the area of open water diminishes and floodplains develop and broaden (Figure 4c). The broadening of coastal floodplains and greater areal extent of the intertidal zone supports more expansive intertidal coastal wetlands (Roy et al., 2001). The ensuing accumulation of organic material within sediments baffles hydrodynamic energy, enhances sedimentation, binds sediments and buffers erosion, creating a feedback that promotes accumulation of organic rich material within substrates (Rogers et al., 2017). Over time, intertidal substrates increase elevation and older organic material (roots) is increasingly buried (McKee, 2011; Woodroffe et al., 2016). Termed "fossil" blue carbon (Rogers et al., 2019b), this preserved carbon will undergo decomposition at rates that are time-dependent and influenced by substrate salinity and oxygen availability. More specifically, decomposition of fossil blue carbon diminishes under anaerobic conditions created by tidal inundation and high ground water levels, whilst methanogenesis is inhibited in the saline substrates that arise from period saline tidal inundation (Duarte et al., 2005; McLeod et al., 2011; Duarte et al., 2013; Macreadie et al., 2017b). Decomposition is also related to variation in sediment characteristics across an estuary: finer grained silts and muds typical of fluvial deltas enhances anaerobic conditions that slow decomposition; sand dominated sediments typical of flood-tide deltas and back barrier zones may have greater aerobic decomposition due to more pore spaces (Saintilan et al., 2013; Kelleway et al., 2016). Contemporary root material is generally restricted to the rooting zone of living vegetation; for mangroves, this is typically to depths of less than 1 m, and may be much shallower for grasses and herbs typical of saltmarshes.

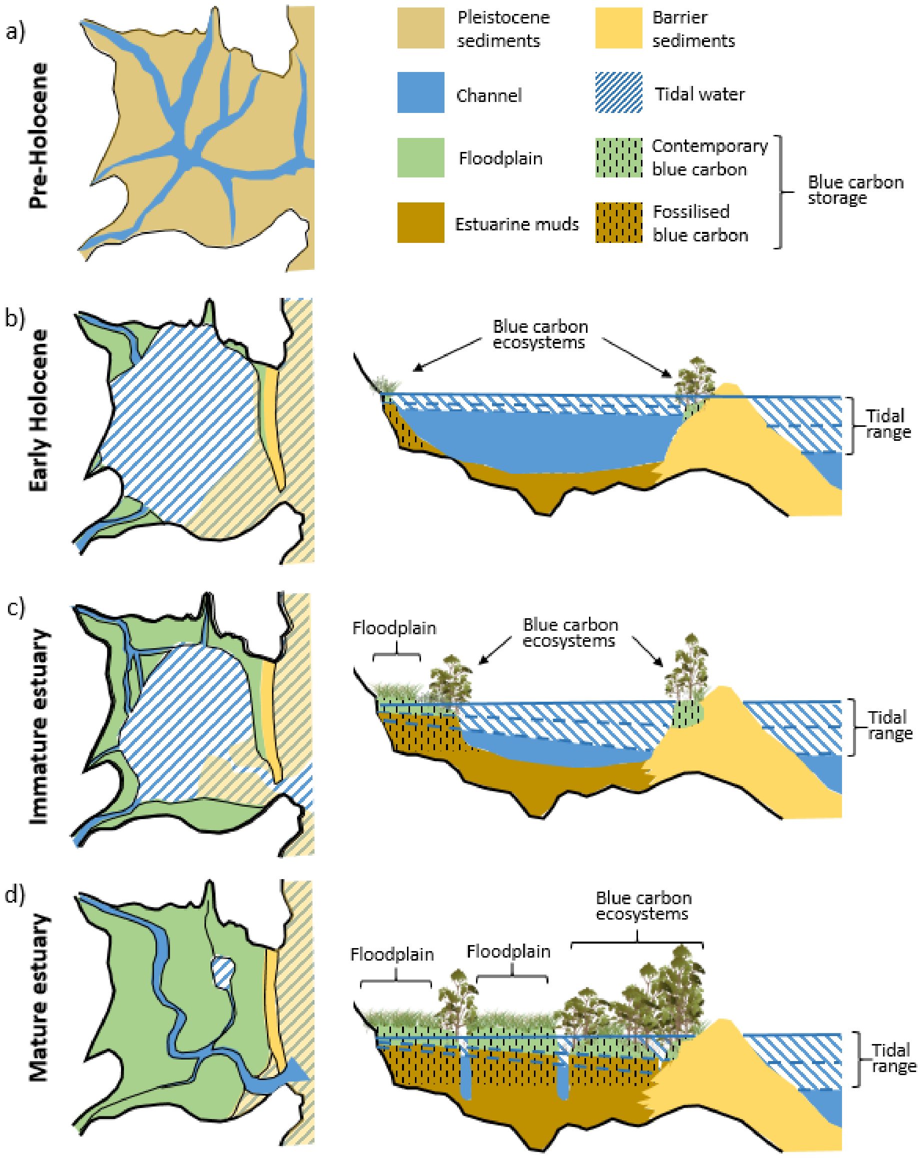
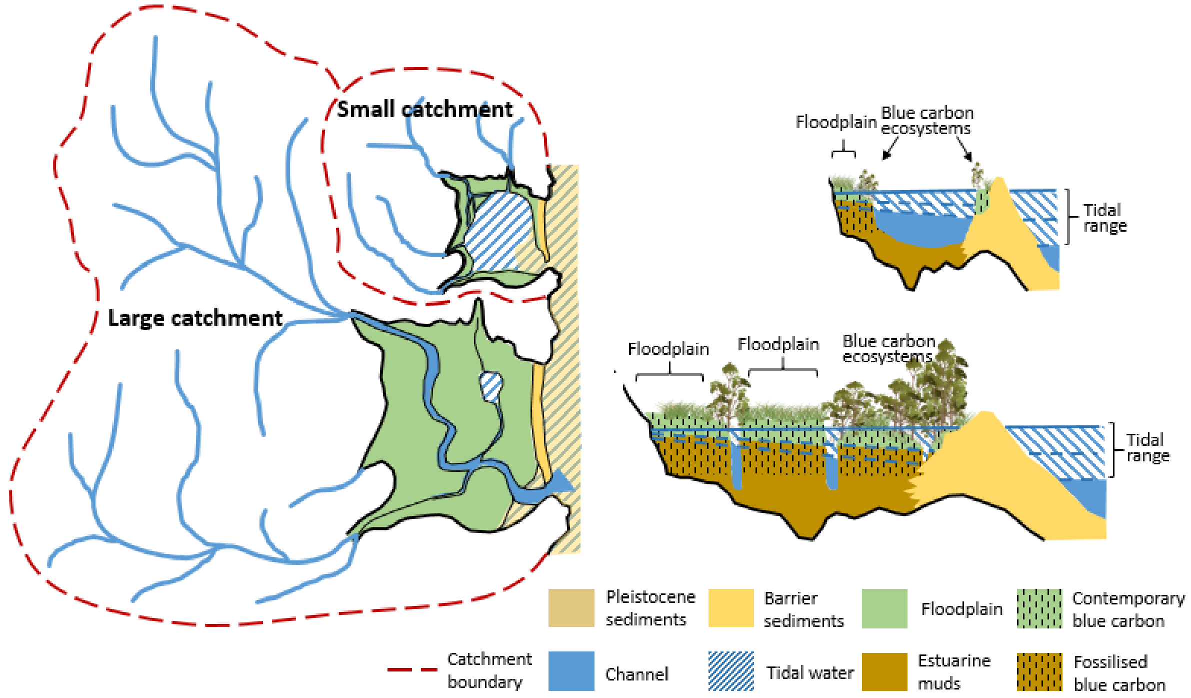


Figure 4: Conceptual models of the evolution of wave-dominated estuaries from the a) pre-Holocene, b) early-Holocene, and eventually to c) immature and d) mature stages of infilling with sediments; and the influence of estuary maturity on blue carbon ecosystem extent, and carbon storage. Adapted from Roy et al. (2001).

In the final stages of maturity, open waters are restricted in extent and channels traverse floodplains comprising of sediments that have infilled coastal valleys since the early Holocene (Figure 4d) (Roy, 1984; Roy et al., 2001). Coastal wetlands will be restricted to the intertidal zone and freshwater wetlands will occur where groundwater is at or near the surface, and fossil blue carbon that has accumulated within substrates over the Holocene may have had considerable time to undergo diagenesis (Rogers et al., 2019a). As tides deliver sulfates to substrates over millennia, ‘fossil’ blue carbon stores may convert to acid sulfate soils when exposed to aerobic conditions (Rosicky et al., 2004; Johnston et al., 2016);

preservation of saline anaerobic conditions serves to both preserve fossil blue carbon and prevent development of acid sulfate soils. Estuaries in mature stages tend to have the most extensive distribution of intertidal coastal wetland vegetation and broad coastal floodplains with freshwater wetlands; however, seagrass vegetation is restricted to channels (Roy et al., 2001), often where hydrodynamic energy may limit their growth.

Considerable variation in estuary size, waterbody area and catchment area occurs along the coastline of southeastern Australia. Of particular note is the high frequency of intermittently closed and open lakes and lagoons, commonly referred to as ICOLLS (Haines, 2006; Haines et al., 2006; Maher et al., 2011). These intermittent estuaries, approximately 70 of the 135 estuaries of NSW, occur in catchments that are relatively small in comparison to the estuary waterbody area, and may be exposed to above average wave energy at the coast. The combination of lower catchment flows from small catchments and higher wave energy facilitate episodic closure of estuary entrances. The distribution of coastal wetland vegetation and blue carbon services has been correlated with catchment area whereby conditions favourable for blue carbon generation is positively correlated with catchment area (Rogers et al., 2019b). Catchment area also influences sediment availability and supply to estuaries, with infill over the Holocene typically greater when catchments are large; accordingly, wave-dominated estuaries in the largest catchments have been classified as mature (Figure 5).



Large catchment → Mature wave-dominated estuary

- Larger bedrock valley volume
- More sediment supply from catchment
- High sediment infill and mature stages
- Expansive alluvial and estuarine floodplains
- More fossil blue carbon
- Less seagrass, more mangrove and saltmarsh
- More freshwater wetlands

Small catchment → Intermittent estuary (ICOLL), or immature estuary

- Smaller bedrock valley volume
- Less sediment supply from catchment
- Immature stages due to less infill
- Entrance may intermittently close, influencing tidal exchange, salinity, water levels, vegetation composition
- Less fossil blue carbon
- Less mangrove and saltmarsh, more seagrass

Figure 5: Conceptual model of the influence of catchment size on estuary function, blue carbon ecosystem extent and carbon storage.

2 Methods

2.1 Approach

The indicator based approach developed by (Rogers et al., 2019b) was applied in ARCGIS. This approach accounted for variation in processes influencing blue carbon across three timescales relevant for management of blue carbon within coastal landscapes:

i) the geological timescale pertains to carbon that has accumulated within Quaternary sediments, termed fossil blue carbon;
ii) contemporary blue carbon is associated with the distribution of mangrove forests and saltmarshes; and
iii) future blue carbon pertains to the ongoing permanency of stored and contemporary blue carbon but does not explicit indicate carbon additionality that may occur as coastal wetlands adjust to sea-level rise.

This approach largely focusses on carbon that accumulates within coastal Quaternary environments and presumes that the bulk of stored carbon arises from the preservation of carbon associated with mangrove and saltmarsh habitats. This carbon includes both autochthonous sources sequestered in situ by marine vegetation and allochthonous sources imported from elsewhere in the catchment and preserved in substrates of blue carbon ecosystems. The contribution of allochthonous carbon to storage within blue carbon ecosystems is not typically substantial (Saintilan et al., 2013) and since preservation of allochthonous carbon within blue carbon ecosystems arises from the anaerobic conditions occurring within intertidal habitats, it is often considered to be blue carbon. Some carbon included in the assessment may be associated with coastal barriers and may not by associated with mangroves and saltmarshes, but should be regarded as blue carbon given their marine connection. Some surficial carbon on coastal floodplains may be associated with supratidal forests and this is reasonable given their landward connection to tidal inundation. Supratidal forests are increasingly considered to be blue carbon habitats as occasional waterlogging and saline substrate conditions typical of blue carbon habitats enhances carbon preservation in these environment (Adame et al., 2020). Excluding other carbon sources, such as surficial carbon associated with agriculture and farming land-use is difficult, but fortunately this carbon makes a relatively low contribution to carbon storage given the low biomass and preservation within substrates. The outcome of these caveats is: i) at the geological timescale, all carbon within coastal Quaternary sediments is presumed to be preserved allochthonous or autochthonous blue carbon associated with mangrove, saltmarsh and seagrass sediments; ii) at the contemporary timescale blue carbon is delimited to the carbon stored within the intertidal zone; and iii) future blue carbon focuses on long-term storage capacity of blue carbon that has accumulated over geological and contemporary timescales.

This approach uses readily accessible spatial data sets that are reclassified and adapted to create raster datasets that indicate the present day capacity for carbon storage, preservation, generation and permanency across coastal landscapes. A blue carbon indicator (BCI) raster dataset was subsequently generated by combining these rasters together. For the purposes of this study, each of these terms are defined below:

- *Storage* is defined as the volume of blue carbon within coastal Quaternary sediments. Accordingly, estuaries that are more mature and have expansive alluvial and estuarine floodplains are more likely to store larger volumes of fossil blue carbon, whilst coastal barrier sediments have conditions less favourable for blue carbon storage
- *Preservation* is defined as the capacity for coastal blue carbon decomposition to be inhibited due to saline anaerobic conditions, and for long-term sequestration within soils. Fine-grained sediments typical of alluvial floodplains, fluvial deltas and to some extent estuarine floodplains will inhibit decomposition more than sandy coastal barrier sediments (Saintilan et al., 2013) and carbon will be more concentrated in these regions. Due to significant decline in hydrodynamic energy as tributaries enter estuaries, fluvial deltas are composed predominantly of finer grain sizes (although pro-delta and delta fronts may have highly variable grain sizes), yet are influenced by tidal inundation resulting in saline conditions ideal for ongoing preservation of stored carbon. Coastal barrier sediments that are typically dominated by sands store less carbon due to greater oxidation of sediments (Kelleway et al., 2016) and in some locations, frequent reworking.
- *Generation* is defined as the capacity for existing mangrove forests and saltmarshes to contribute to carbon additionality from living biomass, dead organic material and soil organic carbon. Several studies indicate that carbon addition is greater in mangrove forests than saltmarshes (Chmura et al., 2003; Pendleton et al., 2012), and this is likely due to greater height and biomass of mangroves compared to herbaceous saltmarsh vegetation. In NSW where both ecosystems occur, mangroves forests typically occupy lower positions within the tidal frame than saltmarshes, and their distribution can be defined on the basis of elevation and hydroperiod (Hughes et al., 2019). Additionally, preservation of soil organic carbon within the contemporary range of mangroves has been found to be greater within fine grained sediments of fluvial origin than sandy coastal barrier sediments.
- *Permanency* is defined as the capacity for carbon to be preserved and not reworked under conditions of higher hydrodynamic energy associated with storms and changes to tidal regimes. The permanency of carbon within substrates has been questioned (DeLaune and White, 2012; Kirwan and Mudd, 2012), particularly in the context of increased storminess. This component does not specifically indicate retreat pathways for coastal ecosystems as they respond to sea-level rise. Lower elevations on estuarine shorelines may be exposed to greater hydrodynamic energy due to fetch and wave-action, whilst coastal barrier sediments are more exposed to high wave energy of the open ocean; the exposure of these sediments to higher hydrodynamic energy increases the probability of reworking and poses considerable risk to carbon permanency.

Human activities in coastal landscapes also exert both direct and indirect pressures on blue carbon (McLeod et al., 2011). Rogers et al. (2019b) accounted for this pressure using land-use mapping, with the premise being that natural landscapes are more compatible with storage, preservation and generation of blue carbon, whilst intensive land-use activities are less compatible. They proposed that this approach partly accounts for socio-economic factors that influence blue carbon. In this study, land-use mapping was reclassified based on perceived present day compatibility with blue carbon to generate a blue carbon compatibility (BCC) raster dataset. Combining the BCC and BCI rasters together subsequently provided an indication of blue carbon potential (BCP).

BCI: Blue Carbon Indicator	x	BCC: Blue Carbon Compatibility	=	BCP: Blue Carbon Potential

2.2 Blue carbon resources: BCI, BCC and BCP

Input geological and morphological datasets were used as proxy indicators of blue carbon storage, preservation, generation and permanency. As this study was undertaken at a regional scale and focused on coastal landscapes rather than individual ecosystems, a trade-off between resolution and spatial extent was essential. Accordingly, the primary input datasets were elevation data derived from the Shuttle Radar Topography Mission and Quaternary and bedrock geology mapping.

- *Shuttle Radar Topography Mission* applied interferometric synthetic aperture radar (InSAR) approach to generate digital elevation models globally. The radar system was deployed in February 2000 and collected data for an 11 day period. Data has been processed and gaps filled using data derived from ASTER Global Digital Elevation Model (ASTER GDEM). For Australia, these DEMs derived from SRTM are available at 1 degree arcsecond resolution, equating to a cell size of approximately 30 m x 30 m. For this study, the DEM product, representing ground surface topography with vegetation feature removed, was accessed from Geosciences Australia. As this dataset has the lowest resolution of all input datasets, all subsequent datasets were converted to this resolution and cells positions aligned to this dataset. The SRTM-DEM does not reliably indicate elevations below 0 m AHD (Australian Height Datum); consequently, the first-pass assessment focused only upon landscape surfaces higher than 0 m AHD. Fortunately, this elevation also approximates the lower limit of mangrove vegetation distribution.
- *Coastal Quaternary and bedrock geology mapping* (Troedson et al., 2004) has been undertaken as part of the NSW Comprehensive Coastal Assessment. This high-resolution mapping classifies depositional units (primarily alluvial plain, estuarine plain and coastal barrier), distinguishes a range of sediment types, processes and geomorphic features (e.g. dune, swamp or channel) and differentiates units by age (i.e. Holocene or Pleistocene). This vector-based dataset can be accessed from a range of online depositories and was reclassified as a raster dataset with resolution and alignment corresponding to the SRTM-DEM dataset.

Spatial analysis was delimited by the extent of the Quaternary geology dataset (Troedson et al., 2004). The coverage of this dataset is restricted to the east by NSW coastline, and to the west by the extent of 1:100,000 map sheets. This relatively arbitrary western limit results in this dataset not covering all of the coastal catchments of NSW, and this limited coverage was particularly evident on the northern coast of NSW where large catchments are substantial and extend farther west than on the southern coast of NSW (Figure 3b, c). As an outcome of this limitation, assessment of blue carbon was undertaken on the basis of catchments within the mapping extent of the Quaternary geology mapping, rather than the full catchment extent. Choropleth raster maps were prepared to indicate blue carbon storage, preservation, generation and permanence. These maps were generated according to geological and morphological criteria and involved reclassifying and adding map layers together according to the cell values in Table 1; this was undertaken using the raster calculator tool on ARCGIS.

To characterise the combined biophysical factors related to blue carbon within coastal landscapes a blue carbon indicator (BCI) choropleth map was prepared using the raster calculator tool to add the prior choropleth maps of blue carbon storage, preservation, generation and permanency together. Resulting cell values ranged up to 12. To assist with interpretation of the BCI map and reduce bias from classification, the generated choropleth map was reclassified to produce a final BCI map using the equal interval classification, with classes labelled:

- High when cell values were greater than 9;
- Moderately high when cell values were 7 – 8;
- Moderate when cell values were 6;
- Moderately low when cell values were 4 – 5;
- Low when cell values were 3; and
- Nil when cell values were zero – 2 (i.e. no blue carbon likely).

Socio-economic factors may provide additional benefit or risk for blue carbon storage, preservation and generation. Spatial variation in socio-economic factors is likely to be significant, but is not available in a format that aligns with the pixel based approach used in this study. For this reason, we initially considered the influence of land-use on blue carbon by comparing the area of each BCI class to the area of land-use categories; this aided identifying the land-use classes most compatible with blue carbon. The additional benefits or risks associated with land-use was incorporated by converting vector-based land-use maps to raster datasets and the basis of major land-use categories (Accessed at the NSW Government environmental data portal: www.seed.nsw.gov.au). Using the 2017 land-use map, land-use was reclassified as a raster dataset to have a resolution and alignment corresponding to the SRTM-DEM, and cell values were adjusted based on the perceived compatibility of land-use with blue carbon services, as indicated in Table 2. To rationalise blue carbon values and compatibility, BCI and BCC raster datasets were multiplied to provide an overall indication of where opportunities for enhancing or preserving blue carbon services are located. To aid interpretation and reduce bias from the classification, BCP datasets were reclassified using the equal interval classification.

Table 1: Approach applied to determining biophysical indicators of BCI including storage, preservation, generation and permanency within estuaries. In combination, these factors were used to generate BCI maps.

BCI Component	**Geomorphic Indicator**	**Description of indicator**	**Cell Label (Value)**	**Cell description**
Storage	Elevation, Geology (Sedimentary and bedrock)	Mature estuaries have larger volume of sediment accumulated over the Holocene compared to immature estuaries Quaternary sediments in mature estuaries have more areas with low slopes (low topographic relief) Finer grained sediments associated with alluvial and estuarine plains store more carbon than sandy sediments associated with coastal barriers	High (3)	Alluvial plain/Estuarine plain + elevation 2-5m
			Moderate (2)	Alluvial plain/Estuarine plain + elevation 0-2m; or Alluvial plain/Estuarine plain + elevation >5m
			Low (1)	Coastal barrier
			Nil (0)	Bedrock geology
Preservation	Geology (Sedimentary and bedrock)	Estuarine sediments exhibits ideal anaerobic and saline conditions for carbon preservation Alluvial sediments increasingly brackish Marine sediments increasingly oxidized or reworked	High (3)	Estuarine plain sediments
			Moderate (2)	Alluvial plain sediments
			Low (1)	Coastal barrier sediments
			Nil (0)	Bedrock geology
Generation	Elevation, Geology (Sedimentary and bedrock)	Lower intertidal areas support mangrove; upper intertidal areas support saltmarsh Saltmarsh in fluvial environments have higher generation capacity than estuarine and marine environments NB: macrophyte mapping was not used due to inconsistencies in accuracy between estuaries.	High (3)	Quaternary deposits + elevation 0-1 m
			Moderate (2)	Alluvial plain + elevation 1-5 m
			Low (1)	Coastal barrier/estuarine plain + elevation 1-2 m
			Nil (0)	Bedrock geology
Permanency	Elevation, Geology (Sedimentary and bedrock)	Lower elevations and shorelines exhibit greater exposure to wave action Marine drivers exhibit history of operating near coastal and estuarine Quaternary deposits.	High (3)	Coastal barrier/Estuarine plain + Elevation > 5 m; or Alluvial plain
			Moderate (2)	Estuarine plain + Elevation < 5m
			Low (1)	Coastal barrier + Elevation < 5 m
			Nil (0)	Bedrock geology

Table 2: Approach applied to determining the influence of land-use on blue carbon potential and to generate BCC maps.

Major land-use category	**Cell Label (Value)**	**Description of land-use category**
Conservation area	High (3)	Crown reserve, cultural heritage site, foreshore land, marine park, national park, nature reserve, conservation area, riparian reserve, regeneration area, state forest, state recreation area, tree lot
Cropping	Low (1)	Continuous or rotation cropping, or with fixed irrigation system, sometimes within ephemeral wetland or lake, may include large crop areas of fodder, rice, sugar cane
Grazing	Moderate (2)	Occurs in range of landscapes including flood runners, firebreaks, agroforestry, ephemeral wetland, native vegetation, riparian land, irrigated pastures, rangelands, cleared land, and grassland
Horticulture	Low (1)	Plantations of banana, bamboo, eucalypt, cut flowers, grass, nursery, olives, orchards, tea tree, tea, coffee, turf, vegetables, vineyard
Intensive animal production	Low (1)	Poultry, abattoirs, cattery, animal production of beef, dairy, poultry, piggery, horse studs, sale yards
Mining/ Quarrying	Low (1)	Derelict and abandoned mines and quarries, grassland within mining lease, mine and quarry sites, restored mining land
Power generation	Moderate (2)	Energy corridors, abandoned power stations, substations, gas supply, and green power
River drainage system	Moderate (2)	Channels, estuarine waters, dams, lakes and lagoons, evaporation basins, marinas, river training, navigation structure, river channel filled with aquatic vegetation, water supply channel, weir
Special category	Moderate (2)	Beach, cliff, crown reserve with public access, defense utilities, foreshore protection, aboriginal land, levees, sand spits, land in transition
Transport and communication	Low (1)	Airports, railway, communication facilities, roads and road reserves, trig stations, beacons
Tree/shrub cover	High (3)	Hardwood, pine, poplar, rainforest, softwood plantations, native forest, logged and regenerated native forest, native woody shrub, riparian vegetation, tree lot, tree corridor
Urban	Low (1)	Residential, rural residential, landfill, abandoned urban or industrial land, aboriginal settlements, caravan parks, cemeteries, waste dump, recreation, tourism, education
Wetland	High (3)	Floodplain swamp, mangrove, mudflat, oyster leases, saltmarsh freshwater swamp

2.3 Influence of barriers on tidal exchange

Wetland drainage and flood mitigation works have had a profound influence on hydrology, especially hydroperiod and tidal exchange across coastal NSW. It was rationalised that barriers below tidal limits would serve as a tidal impediment and increase risks of loss of blue carbon services. The influence of barriers on tidal exchange was determined by identifying barriers that were located near tidal limits; this required access to data on barriers and tidal limits.

- *Barriers* or instream artificial tidal impediments that may limit blue carbon opportunities were selected from the NSW Government Fish Passage Dataset. This dataset indicates the location of in stream structures or barriers that may influence tidal exchange across NSW. This dataset was provided by the Department of Primary Industries: Fisheries.
- *Tidal limits* were mapped by the NSW government between 1996 and 2005 to aid management of coastal zones and provide a historical baseline on the location of tidal limits for future monitoring programs (MHL, 2012). These tidal limits are provided as latitude and longitude and were converted to a point dataset.

Some manipulation of data was necessary due to geospatial errors in the position of some tidal barriers. A 1 km buffer was identified at each tidal limit, and barriers within this buffer were considered to serve as a tidal impediment. Expert opinion from NSW Government Department of Primary Industries Fisheries officers verified the position of tidal barriers and their effectiveness as a tidal impediment. A full list of creeks and rivers in which barriers were identified to have a significant influence on tidal exchange is provided in Supplementary Table 1.

The ARCGIS Hydrology toolset was applied to the SRTM_DEM to model the flow of water across the surface. The ‘Fill’ tool was used to fill sinks in the SRTM_DEM to remove small depressions, or sinks’ in the dataset that limits the effectiveness of the flow modelling tools. The ‘Flow Direction’ tool was used to create a raster dataset representing direction of flow from each cell to its steepest downslope neighbour. The ‘Flow Accumulation’ tool was used to establish flow paths that were regarded to be rivers, creeks and streams. The ‘Stream Order’ tool was used to identify primary and secondary streams. The position of tidal barriers that had been adjusted based on expert opinion were subsequently used to establish pour points using the ‘Pour Point’ tool; hydrological flow from the catchment above this pour point can subsequently be determined. The ‘Watershed’ tool was subsequently used to delineate watersheds above the tidal impediments using the established ‘Pour Points’. The watershed above each pour point was named according to the tributary that it is positioned on. The watershed above each pour point was then used to extract the area of BCP above each pour point; this indicated the BCP area likely to be influenced by tidal impediments.

2.4 Influence of land-use change

Land-use maps were available for two mapping periods: 2007 and 2017. Whilst some variation in land-use between 2007 and 2017 may arise from mapping errors or be an artefact of different mapping approaches, the time-series mapping does provide the capacity to consider the influence of land-use change on blue carbon resources. Initially changes in land-use extent between the two mapping periods was considered using the zonal statistics tool in ARCGIS. This provided the capacity to consider the extent of area that exhibited no change in land-use class over time, and the extent of each land-use class that changed to another land-use class. Time series BCC maps were also developed for the two mapping periods and the influence of land-use changes was considered by undertaking a raster subtraction of the BCC maps using the raster calculator tool. Time-series BCP maps were also developed to characterise the effects of land-use change on BCP.

2.5 Statistical analyses

The area of BCI, BCC (2007 and 2017) and BCP (2007 and 2017) was calculated for each catchment. The area of BCI, BCC (2017) and BCP (2017) was also calculated for each watershed above a barrier. This conversion provided insight into the tidal impediments that significantly influenced BCP, with the premise being that those with the greatest area should be prioritised for restoration, as there was greater blue carbon benefits achieved by reinstating tidal exchange.

Statistical analyses were initially undertaken to identify whether relationships existed between the generated raster datasets and catchment size using regression analyses. The premise of these analyses was that catchment size was proportional to blue carbon services. These analyses focussed on the extent of high BCI, high BCC and high BCP as total area of BCI, BCC and BCP largely corresponds to the extent of Quaternary geology mapping and serves little benefit for decision making. Full factorial analyses of variance were also used to determine whether geomorphological characteristics of estuaries predicted the observed patterns in high BCI, BCC and BCP. Preliminary results indicated that log transformation of catchment area and high BCI, BCC and BCP improved statistical models and all analyses were undertaken using log-transformed data. We specifically tested whether a relationship could be established between the area of high BCI, BCC and BCP, and estuary type. Roy et al. (2001) classified all estuaries in NSW as type: I) Bays, II) tide-dominated estuaries, III) wave-dominated estuaries, IV) intermittent estuaries, and V) freshwater bodies. As type-I estuaries were not included in the study area, there was only 1 type-II estuary, and two type V estuaries, this analysis focussed on differences arising between estuary types-II and IV. In doing so, this analysis effectively considers the influence of estuary or catchment size on blue carbon. We also tested the relationship between the area of high BCI, BCC and BCP, and estuary maturity. Estuary maturity has also been identified by Roy et al. (2001) with each estuary classified as: A) youthful, B) intermediate, C) semi-mature, or D) mature. Analyses were undertaken on all estuaries within the study area, and separated into analyses focussed on the north coast and south coast estuaries.

3 Results

3.1 *Blue carbon resources: BCI, BCC and BCP*

The Clarence and Richmond Rivers of the NSW North Coast generally had the greatest area of high storage, preservation, generation and permanency (Table 3). Whilst four of the 10 largest rivers by catchment are located on the South Coast of NSW (i.e. Shoalhaven, Bega, Tuross and Clyde), it was only the Shoalhaven River that was found to have reasonably high storage (8th highest), generation (6th) and permanency (10th). Consequently, the greatest are with high BCI occurs predominantly in catchments of the NSW North Coast catchments (Figure 6, Table 4). Detailed quantification of blue carbon storage, preservation, generation and permanency are provided in Supplementary Table 2.

Table 3: Catchments (area in hectares) with the greatest area with high scores for storage, preservation, generation and permanency.

Rank	Catchment (Area, ha)	High Storage (Area, ha)	High Preservation (Area, ha)	High Generation (Area, ha)	High Permanency (Area, ha)
1	Clarence River (2218742)	Clarence River (22980)	Clarence River (8651)	Clarence River (9149)	Richmond River (136290)
2	Hunter River (2141399)	Richmond River (21621)	Richmond River (7498)	Macleay River (6284)	Clarence River (86753)
3	Macleay River (1131867)	Hunter River (9874)	Manning River (5555)	Hunter River (5672)	Manning River (53118)
4	Manning River (815922)	Manning River (7233)	Hastings River (5516)	Richmond River (5443)	Macleay River (49734)
5	Shoalhaven River (711772)	Tweed River (5461)	Hunter River (5293)	Manning River (4879)	Hastings River (42205)
6	Richmond River (690022)	Macleay River (5001)	Macleay River (5219)	Shoalhaven River (3860)	Hunter River (41478)
7	Hastings River (368853)	Hastings River (4990)	Wallis Lake (4042)	Hastings River (3368)	Wallis Lake (32139)
8	Bega River (194021)	Shoalhaven River (4700)	Tilligerry Creek (3791)	Wallis Lake (2106)	Myall River (25027)
9	Tuross River (182928)	Wallis Lake (2774)	Tweed River (3166)	Tweed River (1796)	Nambucca River (17058)
10	Clyde River (174046)	Bellinger River (2044)	Port Stephens (2990)	Myall River (1505)	Shoalhaven River (15452)

High BCC was greatest in extent in the catchments of the Richmond and Clarence Rivers, and catchments with the greatest area of high BCC were on the north coast (Table 4). For the majority of catchments the high category of BCC generally relates to floodplain area and correlates with catchment size. A particular exception is the Richmond River which has a floodplain area similar in size to the Clarence River, yet its catchment area is approximately one third the size of Clarence River (Figure 7). The combination of BCI and BCC meant that the most extensive high BCP was largely restricted to estuaries of the NSW North Coast (Figure 8, Table 4). Detailed quantification of BCI, BCC and BCP is provided in Supplementary Table 3.

Table 4: Catchments (area in hectares) with the greatest area of high BCI, high BCC and high BCP.

Rank	High BCI (Area, ha)	High BCC (Area, ha)	High BCP (Area, ha)
1	Clarence River (39445)	Richmond River (43471)	Clarence River (7877)
2	Richmond River (29860)	Clarence River (36345)	Richmond River (4711)
3	Hunter River (17841)	Hastings River (23635)	Hunter River (3365)
4	Macleay River (13302)	Myall River (19472)	Macleay River (3361)
5	Manning River (11829)	Macleay River (19092)	Hastings River (2291)
6	Hastings River (8127)	Wallis Lake (16744)	Shoalhaven River (1388)
7	Tweed River (8059)	Hunter River (13136)	Wallis Lake (1313)
8	Shoalhaven River (7806)	Manning River (11066)	Manning River (845)
9	Wallis Lake (3594)	Port Stephens (8110)	Port Stephens (596)
10	Nambucca River (3049)	Tilligerry Creek (7347)	Myall River (584)

The rivers with the largest floodplain areas, that is the Clarence and Richmond Rivers, overwhelming have the highest areas for storage, preservation, generation and permanency of blue carbon, and this results in a large total BCI area, as indicated in Figure 9 for the Clarence River. The broad coastal floodplains of these rivers are ideal for agriculture and other land-uses, and this is reflected in high total BCC scores; however, there still remains large areas within these catchments that have high BCC area (Figure 10). The outcome of this is that high BCP area is associated primarily with the larger catchments and particularly those with large floodplains. Only one estuary on the south coast, the Shoalhaven River, is reported to have large area of high BCP, and the striking absence of south coast estuaries likely relates to the predominance of smaller estuaries, particularly ICOLLs (Table 4).

Comparison of the area of land-use classes in 2017 with associated BCI indicates an unsurprising relationship between land use classes of wetlands, and river and drainage systems, and high BCI area (Figure 11). However, a significant area of high BCI area coincides with cropping land-use, and this indicates that significant opportunities for restoration of blue carbon services coincides with cropping regions.

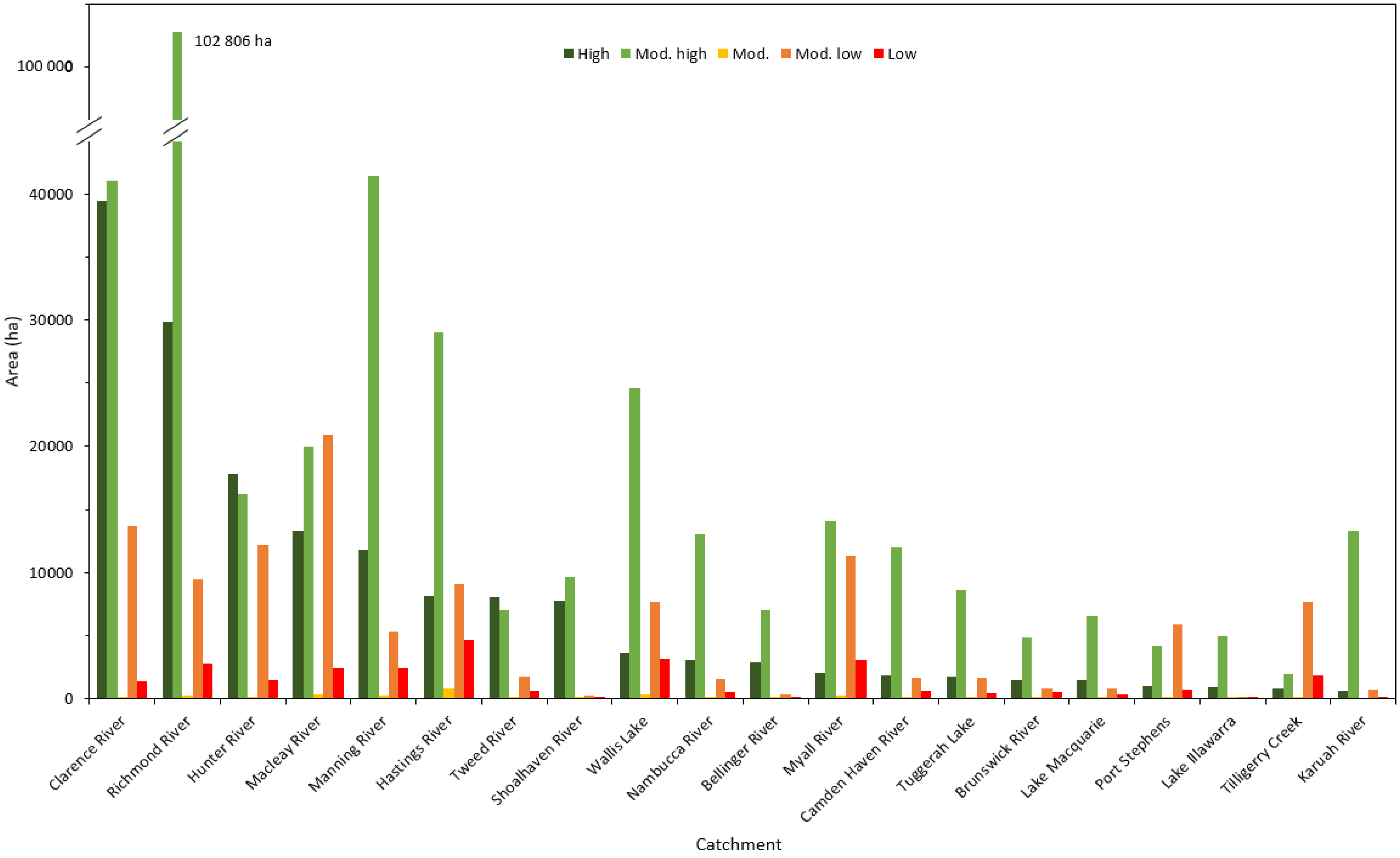


Figure 6: BCI area (hectares) of low, moderately low, moderate, moderately high and high value within catchments with large BCI area (i.e. top 20 catchments based on BCI area). Catchments have been ranked on the basis of total BCI area from largest to smallest. See Supplementary Figure 1 for BCI area of all catchments.

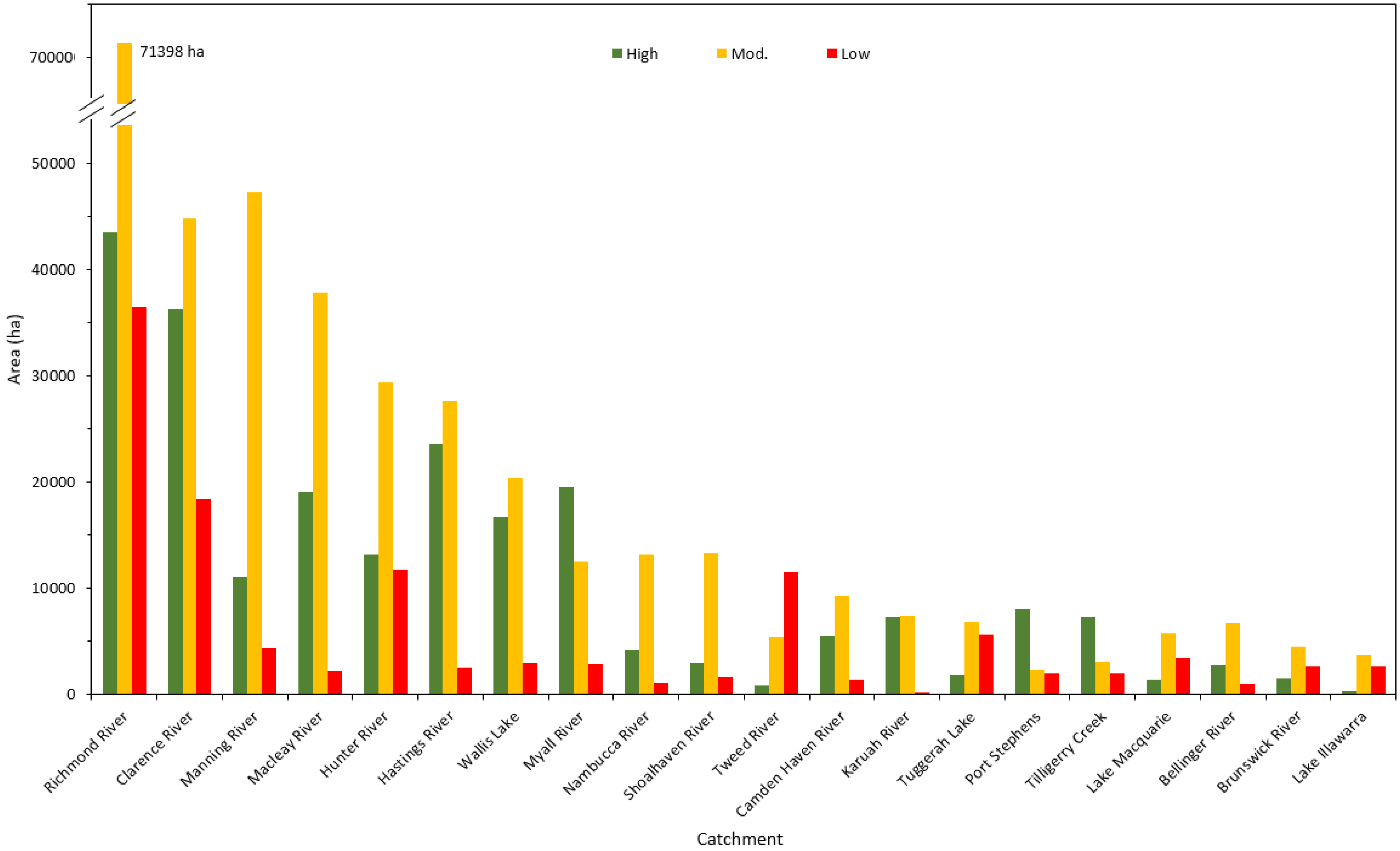


Figure 7: BCC area (hectares) of low, moderate, and high value within catchments with large BCC area (i.e. top 20 catchments based on BCC area). Catchments have been ranked on the basis of total BCC area from largest to smallest. See Supplementary Figure 2 for BCC area of all catchments.

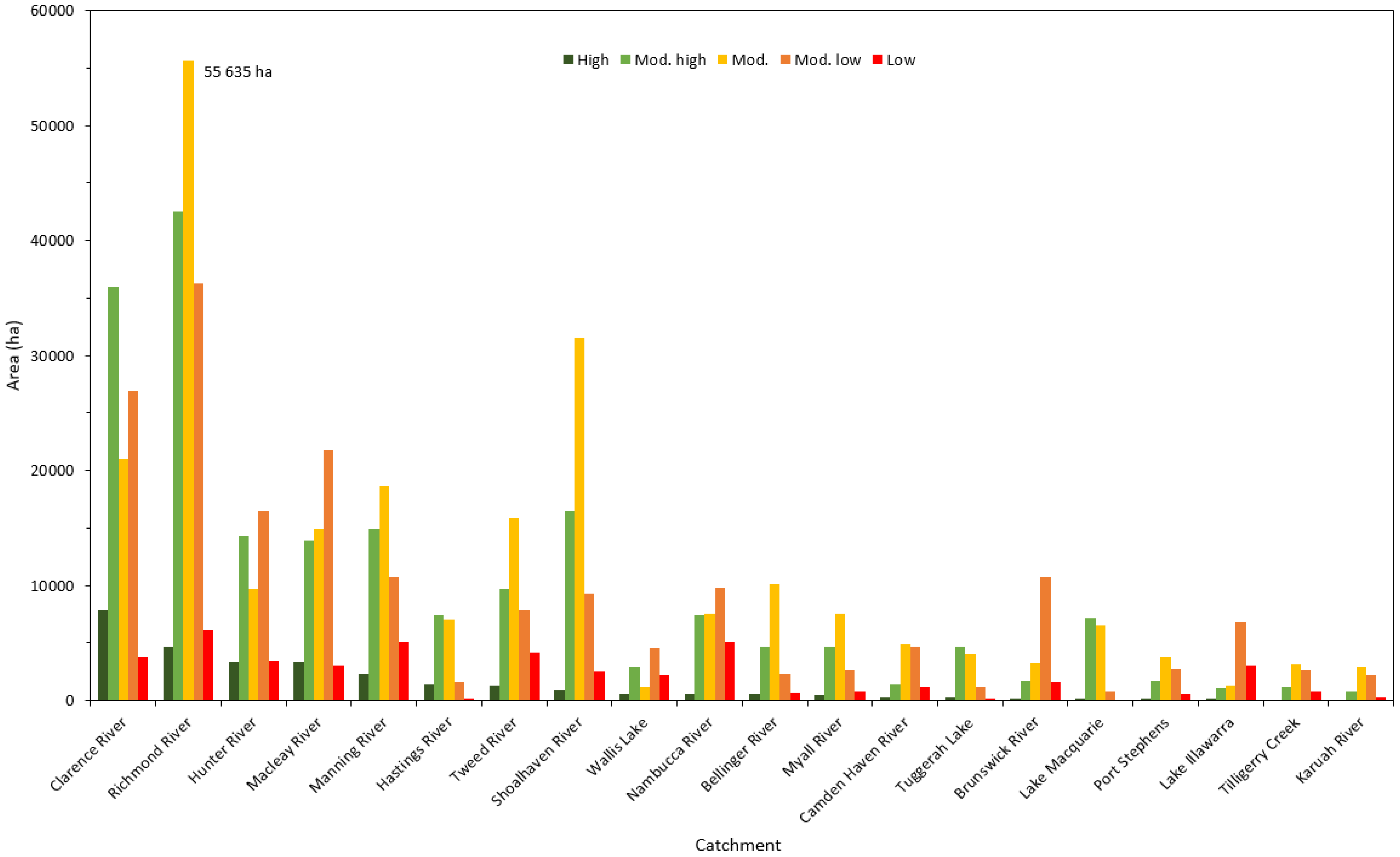


Figure 8: BCP area (hectares) of low, moderately low, moderate, moderately high and high value within catchments with large BCP area (i.e. top 20 catchments based on BCI area). Catchments have been ranked on the basis of total BCP area from largest to smallest. See Supplementary Figure 3 for BCP area of all catchments.

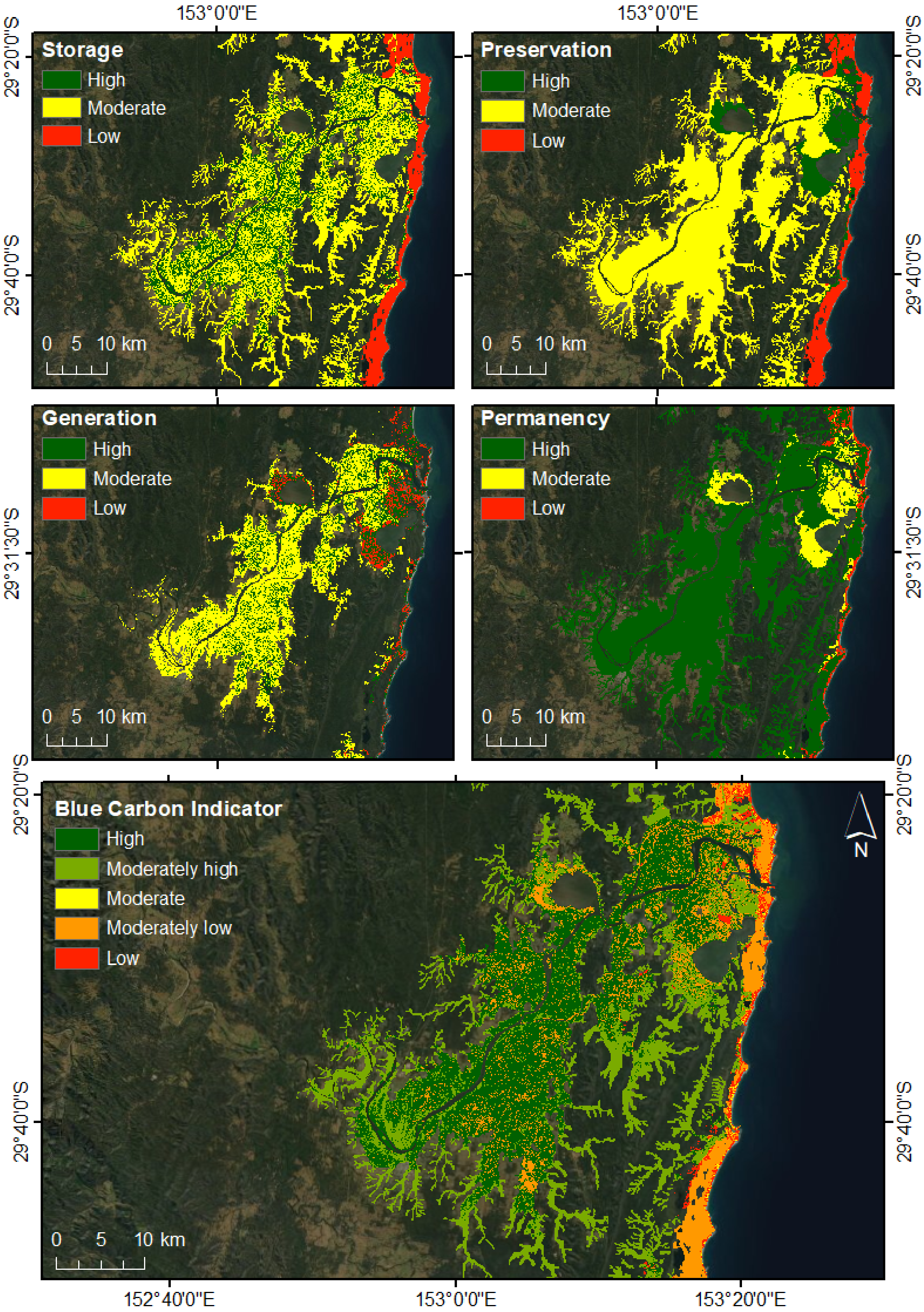


Figure 9: Storage, preservation, generation, permanency of blue carbon and BCI distribution on the Clarence River.

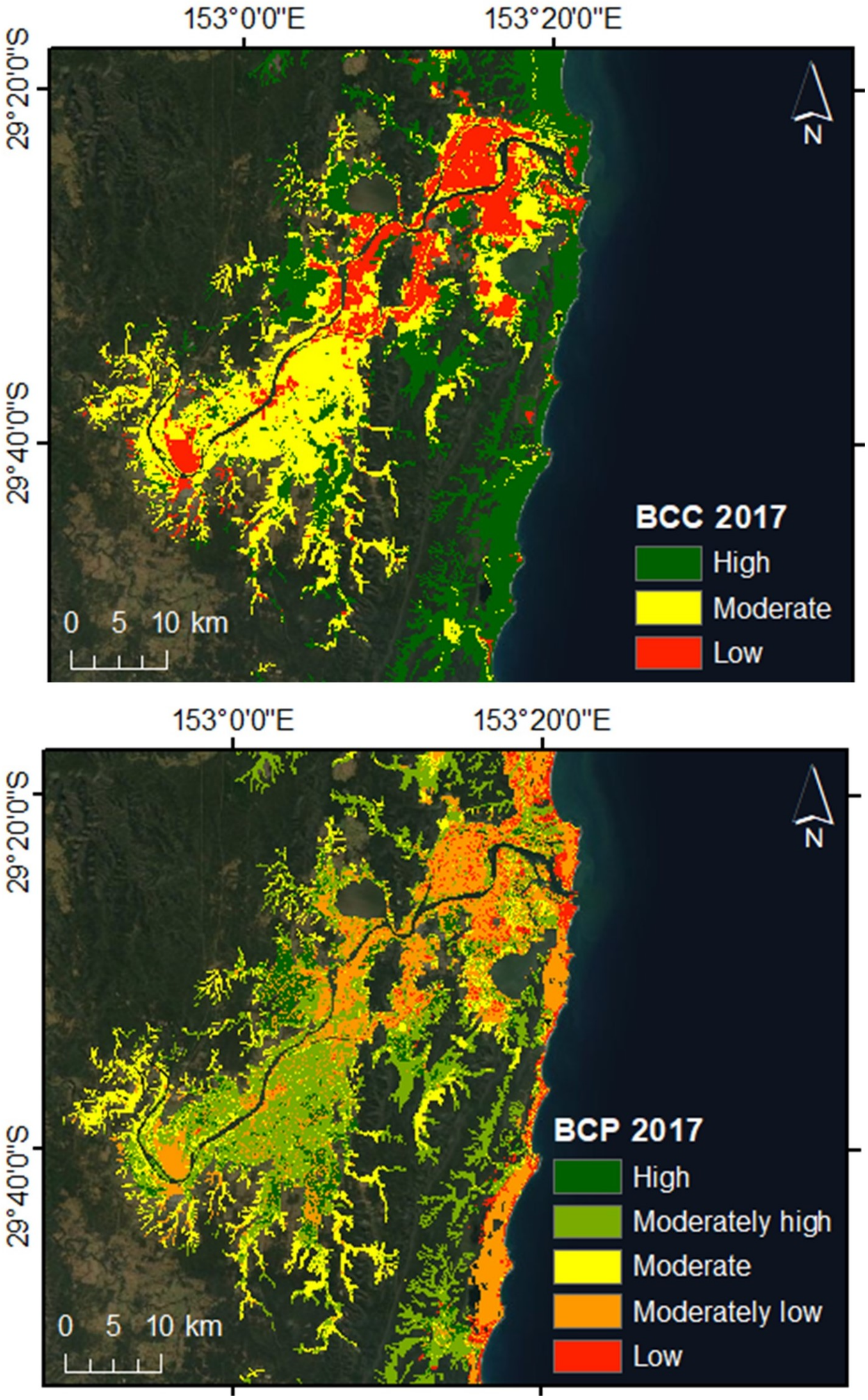


Figure 10: BCC and BCP area on the Clarence River in 2017.

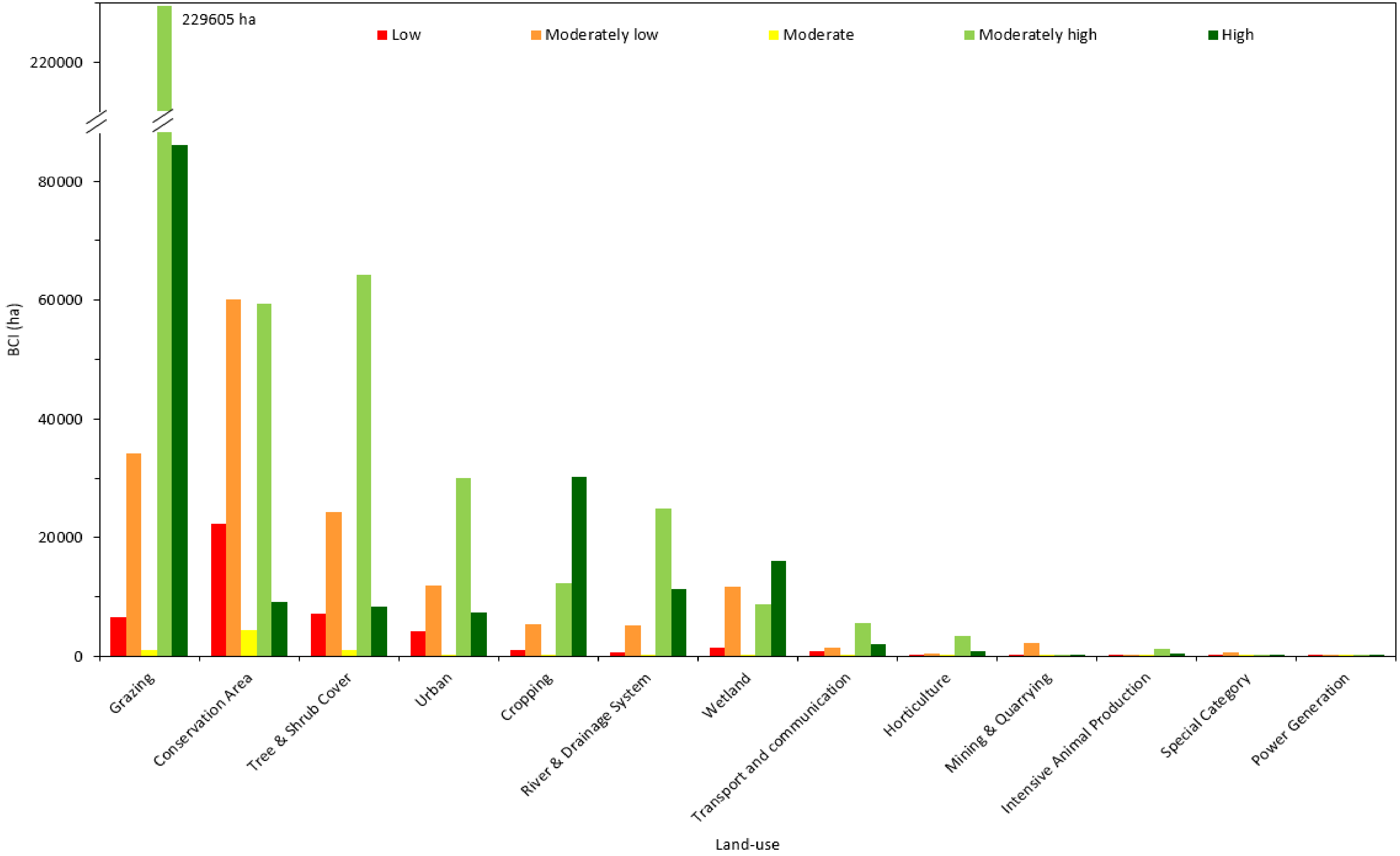


Figure 11: Coincidence of BCI values and land-use across the study area. The greatest extent of total BCI coincided with grazing and conservation areas, whilst cropping had the greatest extent of high BCI area. See Supplementary Figure 4 for BCI area and land-use for all catchments.

Regression analyses confirmed significant positive relationships between catchment area and high BCI, BCC and BCP for all estuaries in the study area (Figure 12 a-c, $p < 0.0001$ for all analyses). The greater proportion of large catchments on the north coast influenced the behaviour of this relationship, and exponential regressions performed significantly better for estuaries of the north coast (Figure 12 d-f, $p < 0.0001$ for all analyses). The predominance of smaller catchments on the south coast likely improved the performance of linear regressions (Figure 12 g-i, $p < 0.0001$ for all analyses). Full factorial analyses that accounted for variation in estuary type and maturity marginally improved upon linear regression analyses, but did not improve relationships when the large catchments of the north coast were incorporated. A detailed summary of regression analysis results are provided in Table 5.

Table 5: Coefficient of determination (r^2), F-ratio and p-value for linear, exponential and full factorial linear models of relationships between catchment area (ha), estuary type (III or IV) and estuary maturity (A, B, C or D), and response variables of high BCI, BCC and BCP area.

Catchment	**Regression**	**Response variable**	**BCI High**	**BCC High**	**BCP High**
North & South Coasts	Linear	r^2	0.7767	0.4845	0.7884
		F-ratio	507.9478	137.2385	543.9484
		p-value	<0.0001	<0.0001	<0.0001
	Exponential	r^2	0.7853	0.4824	0.5229
		F-ratio	504.7016	133.2543	139.1824
		p-value	<0.0001	<0.0001	<0.0001
	Full factorial	r^2	0.7831	0.547	0.7972
		F-ratio	29.5546	9.886	32.1911
		p-value	<0.0001	<0.0001	<0.0001
North Coast	Linear	r^2	0.7661	0.4758	0.784
		F-ratio	193.1959	53.553	214.1552
		p-value	<0.0001	<0.0001	<0.0001
	Exponential	r^2	0.886	0.707	0.7933
		F-ratio	435.3911	142.374	211.1002
		p-value	<0.0001	<0.0001	<0.0001
	Full factorial	r^2	0.7832	0.6268	0.7984
		F-ratio	10.835	5.0392	11.8789
		p-value	<0.0001	<0.0001	<0.0001
South Coast	Linear	r^2	0.9581	0.5137	0.8272
		F-ratio	1942.493	89.7971	406.8621
		p-value	<0.0001	<0.0001	<0.0001
	Exponential	r^2	0.6407	0.2894	0.2041
		F-ratio	142.6852	33.4	17.948
		p-value	<0.0001	<0.0001	<0.0001
	Full factorial	r^2	0.9655	0.7575	0.8612
		F-ratio	132.2904	14.785	29.3733
		p-value	<0.0001	<0.0001	<0.0001

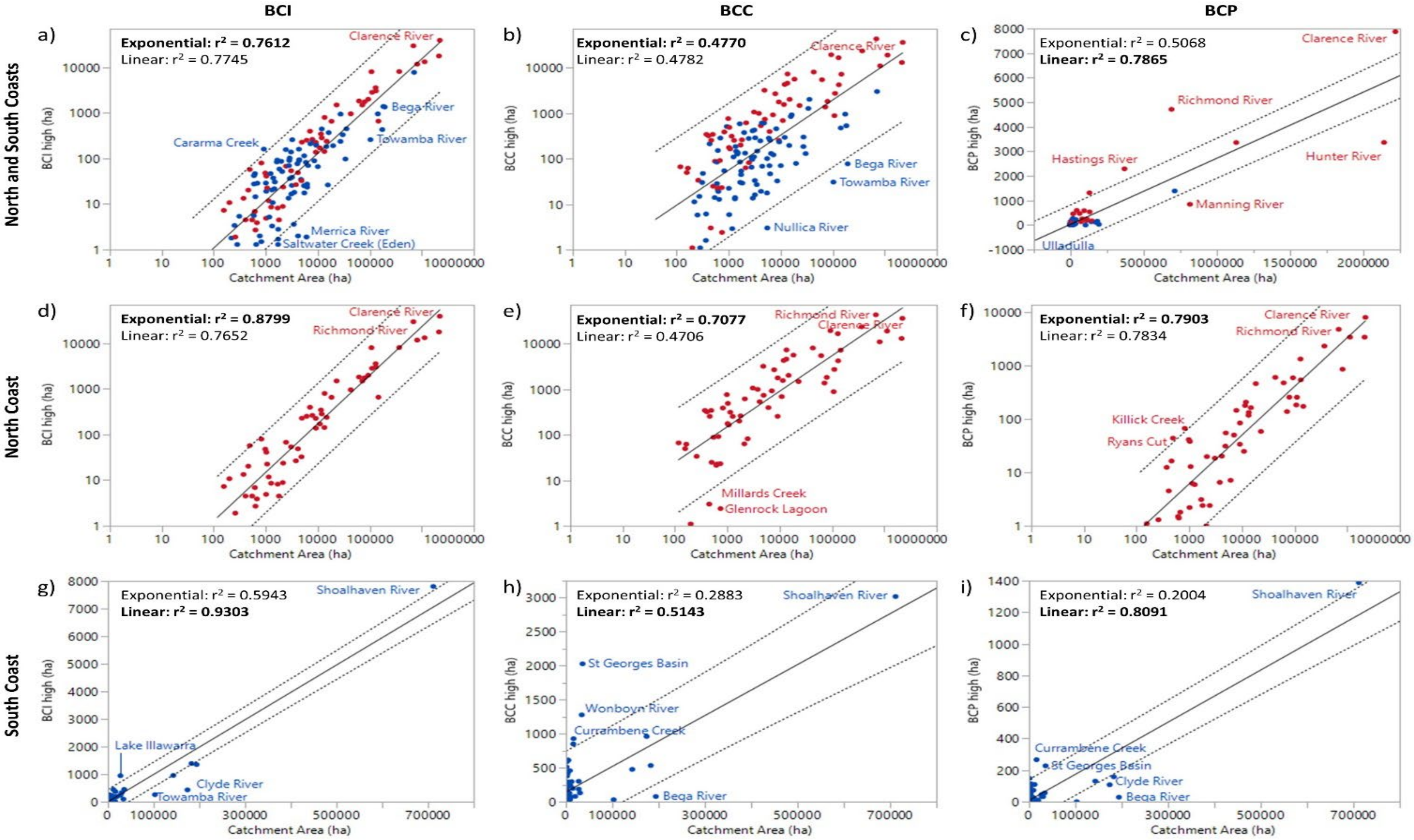


Figure 12: Relationships between: catchment area on the north and south coasts and a) high BCI, b) high BCC, and c) high BCP; catchment area on north coast and d) high BCI, e) high BCC, and f) high BCP; and catchment area on the south coast and g) high BCI, h) high BCC, and i) high BCP. Catchments on the north coast indicated by red points, and catchments on the south coast indicated by blue points. Dashed lines indicate 95% confidence intervals of individuals.

3.2 Influence of barriers on tidal exchange

Approximately 6074 ha of high BCP area occurs in watersheds above tidal impediments, of which 5154 ha is situated in the north coast and 920 ha is situated on the South Coast of NSW. The most extensive areas of high BCP in a watershed occurs on Belmore River (1240 ha), Tuckean Broadwater (1199 ha) and Clybucca Creek (866 ha). These watersheds also have the most extensive area of all BCP classes (Table 6), and regions where significant gains in blue carbon services may be achieved through management of barriers.

Tuckean Broadwater exhibits extensive high and total BCI, and this largely arises from a predominance of moderate to high cell values across storage, preservation, generation and permanency layers (Figure 13). Coupled with an extensive area high moderate to high BCC, Tuckean Broadwater represents an ideal barrier for management, re-engineering or removal to improve blue carbon services (Figure 14). The potential for high blue carbon services should be a significant factor for management of barriers at Clybucca Creek, Belmore River, and to a lesser extent Wallamba River and Crookhaven Creek (Figure 15). For detailed quantification of the area of blue carbon storage, preservation, generation, permanency, BCI, BCC and BCP by watershed see Supplementary Table 4 and Supplementary Table 5.

Table 6: Tributaries with the largest area above a barrier of high BCI, total BCI, high BCC, total BCC, high BCP and total BCP. Catchments indicated in bold.

Rank	High BCI (Area, ha)	Total BCI (Area, ha)	High BCC (Area, ha)	Total BCC (Area, ha)	High BCP (Area, ha)	Total BCP (Area, ha)
1	Tuckean Broadwater, Bagotville barrage, Tuckean Wetland, **Richmond** (3253)	Clybucca Creek Menarcobrinni floodgate, Seven Oaks Drain, **Macleay** (8680)	Belmore River, Belmore Swamp, **Macleay** (4870)	Clybucca Creek, Menarcobrinni floodgate, Seven Oaks Drain**, Macleay** (9578)	Belmore River, Belmore Swamp, **Macleay** (1240)	Clybucca Creek, Menarcobrinni floodgate, Seven Oaks Drain, **Macleay** (8680)
2	Crookhaven Creek, Culburra Road floodgate, **Shoalhaven** (2429)	Tuckean Broadwater, Bagotville barrage, Tuckean Wetland, **Richmond** (7747)	Clybucca Creek, Menarcobrinni floodgate, Seven Oaks Drain **Macleay** (3744)	Tuckean Broadwater Broadwater, Bagotville barrage, Tuckean Wetland**, Richmond** (8155)	Tuckean Broadwater, Bagotville barrage, Tuckean Wetland, **Richmond** (1199)	Tuckean Broadwater, Bagotville barrage, Tuckean Wetland, **Richmond** (7747)
3	Clybucca Creek Menarcobrinni floodgate, Seven Oaks Drain, **Macleay** (2415)	Belmore River, Belmore Swamp, **Macleay** (7205)	Tuckean Broadwater, Bagotville barrage, Tuckean Wetland**, Richmond** (2528)	Belmore River, Belmore Swamp, **Macleay** (7808)	Clybucca Creek Menarcobrinni floodgate, Seven Oaks Drain, **Macleay** (866)	Belmore River, Belmore Swamp, **Macleay** (7205)
4	Belmore River, Belmore Swamp, **Macleay** (2195)	Wallamba River, Clarksons crossing, **Wallis** (7141)	Kinchela Creek, Swan Pool, **Macleay** (1717)	Wallamba River, Clarksons crossing, **Wallis** (7136)	Crookhaven Creek, Culburra Road floodgate, **Shoalhaven** (587)	Wallamba River, Clarksons crossing, **Wallis** (7136)
5	Southgate/ Alumy Creek, **Clarence** (1400)	Lansdowne River, Lansdowne Weir, **Manning** (3884)	Crawford River Bulahdelah, **Myall** (1120)	Lansdowne River, Lansdowne Weir, **Manning** (3883)	Sportsman Creek, Sportsmans Creek Weir, Everlasting Swamp, **Clarence** (556)	Lansdowne River, Lansdowne Weir, **Manning** (3883)
6	Leddays/ McLeods Creek, **Tweed** (967)	Crookhaven Creek, Culburra Road floodgate, **Shoalhaven** (3666)	The Branch River, **Karuah** (1074)	Crookhaven Creek Culburra Road floodgate, **Shoalhaven** (3688)	Coldstream River**, Clarence** (343)	Crookhaven Creek, Culburra Road floodgate, **Shoalhaven** (3657)
7	Kinchela Creek, Swan Pool, **Macleay** (808)	Kinchela Creek, Swan Pool, **Macleay** (3086)	Crookhaven Creek, Culburra Road floodgate, **Shoalhaven** (896)	Kinchela Creek, Swan Pool, **Macleay** (3131)	Kinchela Creek, Swan Pool, **Macleay** (308)	Kinchela Creek, Swan Pool, **Macleay** (3086)
8	Sportsman Creek Sportsmans Creek Weir, Everlasting Swamp, **Clarence** (740)	The Branch River, **Karuah** (3045)	Sportsman Creek, Sportsmans Creek Weir, Everlasting Swamp, **Clarence** (846)	The Branch River, **Karuah** (3045)	Crookhaven River, Culburra Road floodgate, **Shoalhaven** (199)	The Branch River, **Karuah** (3045)
9	Williams River, Seahams Weir, **Hunter** (658)	Crawford River, Bulahdelah, **Myall** (2246)	Pipeclay Canal, Big Swamp, **Manning** (609)	Mullet Creek, **Lake Illawarra** (2269)	Southgate/ Alumy Creek, **Clarence**(169)	Crawford River, Bulahdelah, **Myall** (2245)
10	Coldstream River, **Clarence** (484)	Mullet Creek, **Lake Illawarra** (2113)	Broadwater Creek, The Broadwater, **Clarence** (527)	Crawford River, Bulahdelah, **Myall** (2263)	Poverty Creek, **Clarence** (157)	Mullet Creek, **Lake Illawarra** (2105)

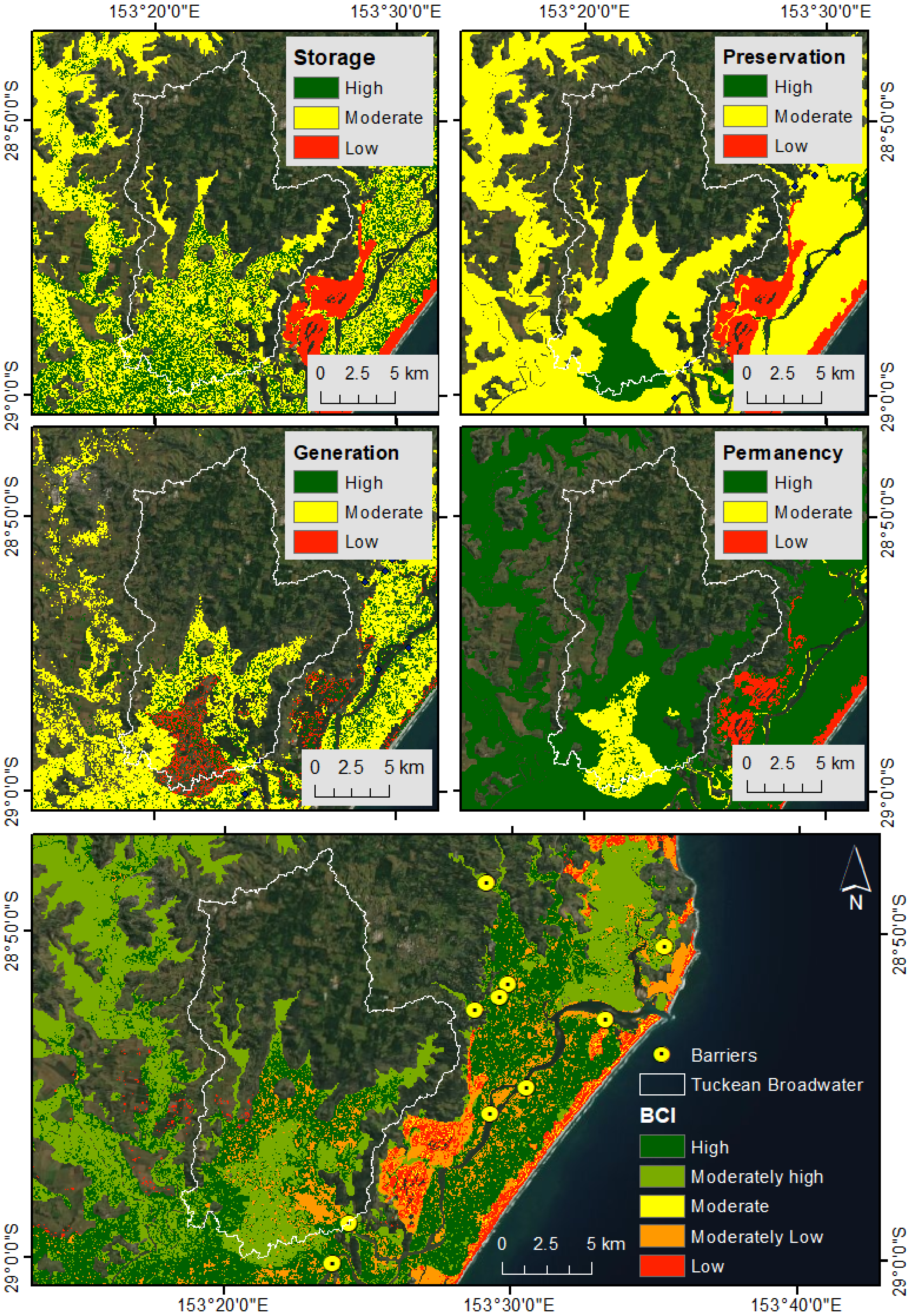


Figure 13: Storage, preservation, generation, permanency and BCI area (ha) within Tuckean Broadwater (indicated by white boundary). This represents a substantial area of high BCI located above a tidal barrier.

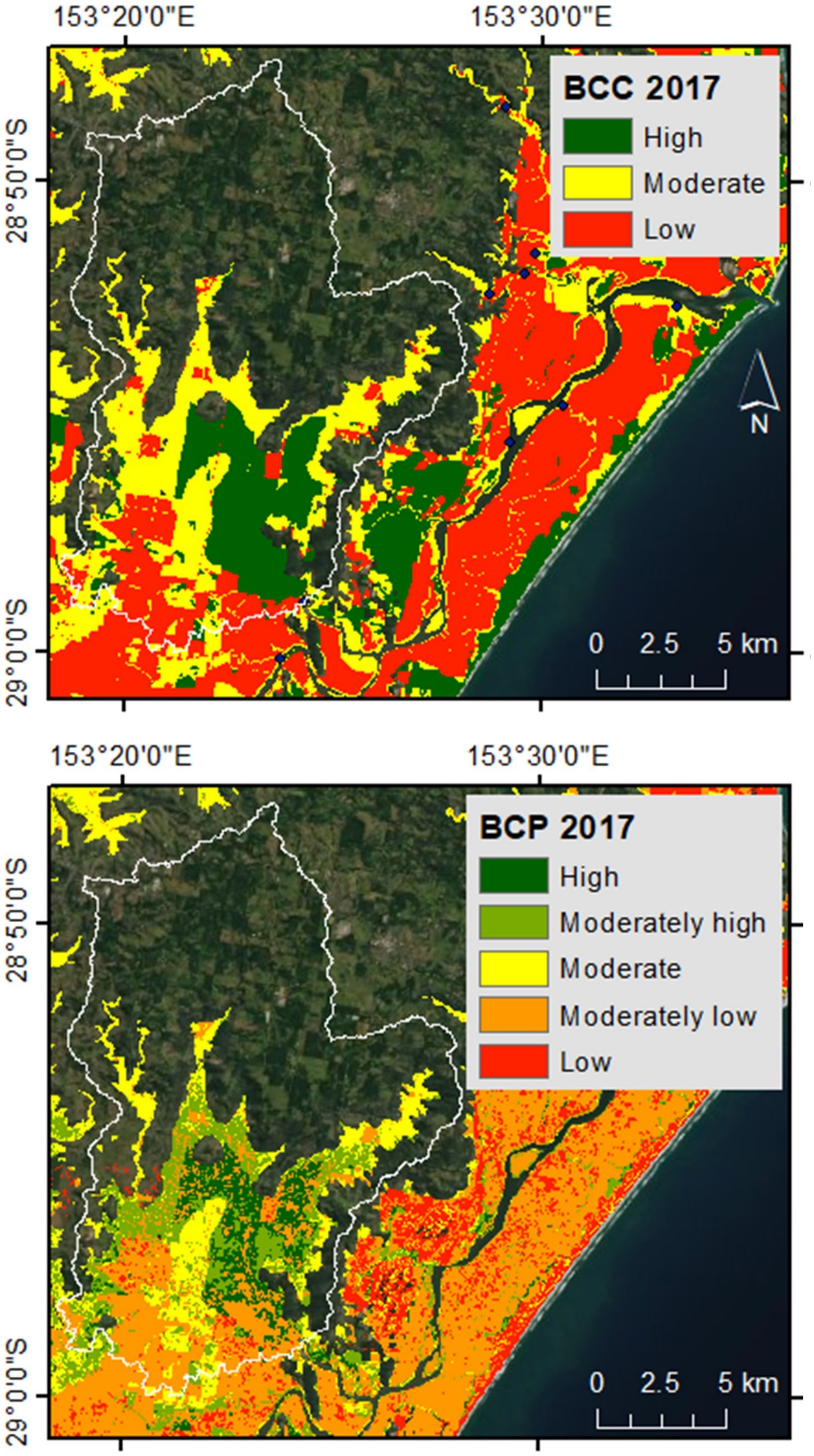


Figure 14: BCC and BCP area within Tuckean Broadwater. This represents a high priority area for restoration.

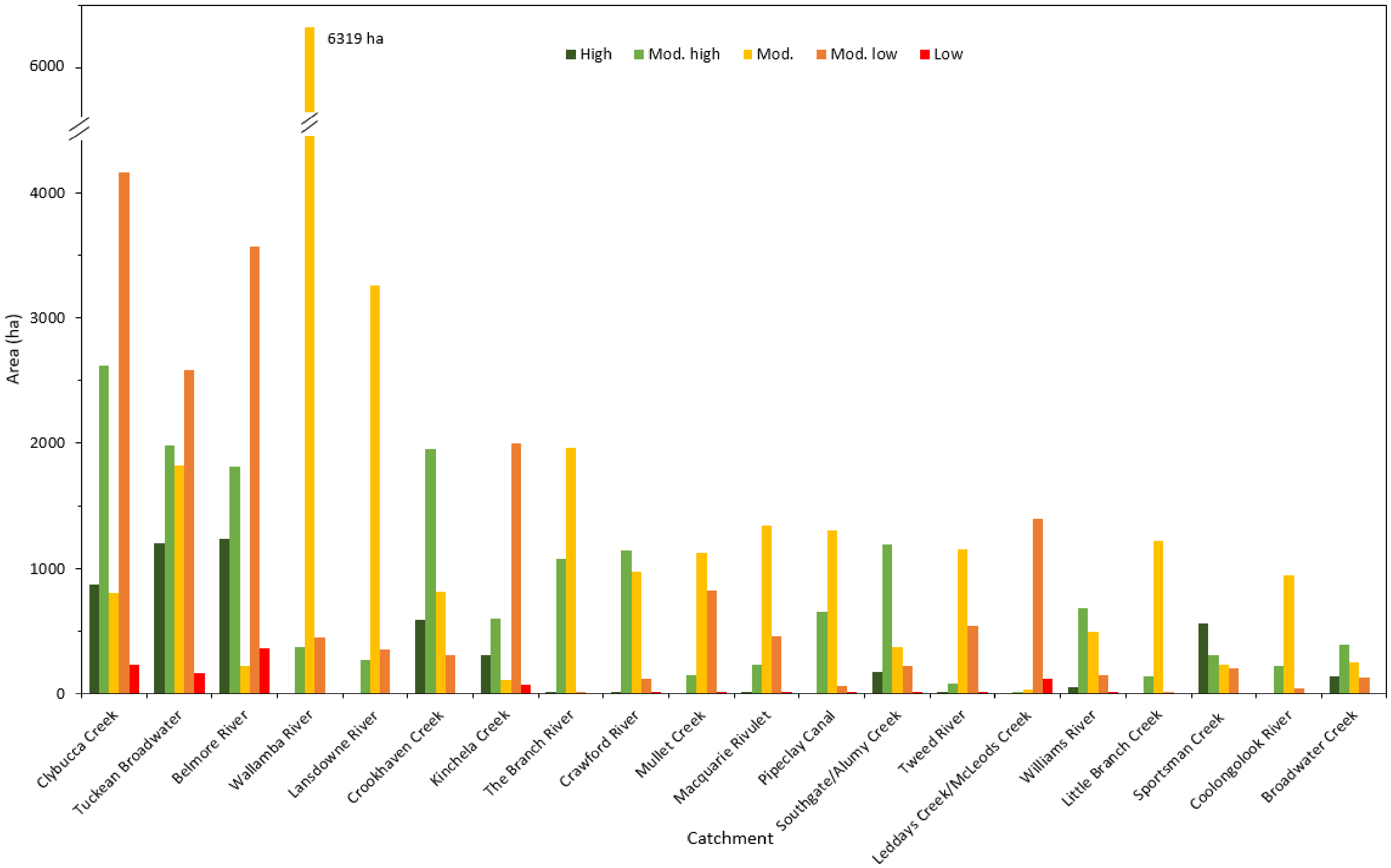


Figure 15: Extent of BCP (in hectares) within watersheds located above a tidal barrier. Areas have been ranked from largest to smallest and figure includes top 20 tributaries based on BCP area within watersheds. See Supplementary Figure 5 for BCP area within watersheds above tidal barriers for all catchments.

3.3 Influence of land-use change on BCC

Changes to land-use occurred between 2007 and 2017 (Table 7); however, for some classes this may be related to different classification approaches between the two mapping periods. This is the likely the case where the change of land-use class is relatively similar, such as the conversion of ‘conservation area’ to ‘river and drainage system’ class, ‘grazing’ to ‘cropping’ class, ‘grazing’ to ‘river and drainage system’ class, and ‘tree and shrub cover’ to ‘conservation area’ class. Of particular note is the conversion of more than 60 000 ha of ‘river and drainage system’, ‘tree and shrub cover’, ‘urban’, and ‘wetland’ to the ‘grazing’ land-use class within all of the catchments. There was also significant conversion of ‘grazing’ to ‘urban’ between 2007 and 2017.

Within the area delineated as having a BCI value, high compatibility values decreased significantly, whilst low and moderate values increased a little. Specifically, the BCC values for low and moderate areas increased by ~4% and ~8%, respectively, but decreased by ~18% in the high BCC category (Table 8). Much of this change was attributed to the conversion of high BCC regions in 2007 to moderate BCC in 2017. This may occur when wetland or natural tree coverage land-use changes to agriculture or grazing. Very little low or moderate BCC areas that were used for grazing in 2007 have transformed into high BCC land-use practices, such as wetland or plantation forest and regeneration of native forests; indicating that potential BCC gains can still be achieved through conservation practices that promote restoration of grazing or agricultural land to current or future blue carbon ecosystems.

Analyses of land-use change indicate that conversion of compatible land-uses to more intensive land-uses, such as cropping and grazing, is containing. In particular, land-use change between 2007 and 2017 had a notable influence on BCP, and these losses were concentrated in areas with high BCC. There was markedly more loss of high BCC extent than gain in BCC extent, estimated to be in the order of ~3600 ha, and ~26 000 ha over the entire study area, respectively. The pattern was reflected in high BCP values with significantly more loss in high BCP extent (~4500 ha) than gain (~1050 ha) (Table 9). The Richmond River catchment exhibited a net increase in high BCC area (increase by 2572 ha), representing a 6% increase on high BCC area between 2007 and 2017 (Figure 16a). However, there was a decline in high BCP in the order of 59 ha. The Myall Lakes exhibited a remarkable decline in high BCC over the 10-year land-use mapping period, decreasing by 3593 ha or 16% (Figure 16b).

Table 7: Change in land-use for each class between 2007 and 2017 within catchments of the study area. Values in red indicate significant changes exceeding 10 000 ha. Areas likely to be related to different classification approaches, and which may not represent actual changes in land-use, are indicated by *.

		2017 Land-use area (ha)												
		Conservation Area	Cropping	Grazing	Horticulture	Intensive Animal Production	Mining & Quarrying	Power Generation	River & Drainage System	Special Category	Transport and communication	Tree & Shrub Cover	Urban	Wetland
2007 Land-use area (ha)	Conservation Area	**126126**	38	1492	9	6	20	10	20512*	10	229	2573	287	2019
	Cropping	20	**39753**	7057	853	137	7	0	930	39	412	80	658	144
	Grazing	1941	10236*	**292377**	1289	1162	160	74	13830*	492	2519	9765	12922	7385
	Horticulture	29	582	1695	**2300**	20	0	0	195	206	61	3640	226	20
	Intensive Animal Production	0	1	213	3	**245**	0	0	24	0	9	2	69	2
	Mining & Quarrying	336	6	1302	17	25	**2298**	47	398	519	36	1085	309	88
	Power Generation	3	0	154	0	0	3	**197**	8	0	3	29	14	1
	River & Drainage System	499	425	12169*	80	488	6	4	**106020**	19	128	878	694	878
	Special Category	4304	71	813	13	3	3	3	520	**13**	43	1169	925	22
	Transport & communication	156	261	3127	30	13	6	4	291	31	**4764**	282	745	138
	Tree & Shrub Cover	12243*	185	17405	220	56	444	88	3855	64	589	**80966**	2010	2006
	Urban	299	236	15575*	117	229	37	26	2448	135	1670	1788	**37908**	430
	Wetland	5062	166	15658	18	12	43	7	5417	75	155	2473	442	**26538**

Table 8: Changes in extent (ha) of BCC classes between 2007 and 2017. Note that this is limited by extent of Quaternary sediments which are a subset of the total catchment and will not correspond to values in Table 7.

		2017 BCC Class		
		Low	Moderate	High
2007 BCC	Low	96925	33223	9291
	Moderate	32076	332551	29091
	High	5603	46661	282722

Table 9: Catchments with a significant gain or loss in high BCC and high BCP between 2007 and 2017.

Rank	**High BCC Gain (Area, ha)**	**High BCC Loss (Area, ha)**	**High BCP Gain (Area, ha)**	**High BCP Loss (Area, ha)**
1	Richmond River (2571)	Myall River (-3593)	Clarence River (458)	Shoalhaven River (-453)
2	Goolawah Lagoon (153)	Lake Macquarie (-2504)	Hunter River (339)	Bega River (-403)
3	Crooked River (140)	Tuggerah Lake (-2295)	Congo Creek (57)	Wallis Lake (-367)
4	Congo Creek (130)	Wonboyn River (-1507)	Currarong Creek (46)	Tuggerah Lake (-356)
5	Currambene Creek (122)	Manning River (-1201)	Macleay River (42)	Lake Macquarie (-306)
6	Currarong Creek (105)	Tuross River (-1133)	Currambene Creek (17)	Nambucca River (-240)
7	Jervis Bay (96)	Wallis Lake (-963)	St Georges Basin (11)	Manning River (-208)
8	Smiths Lake (64)	Bega River (-940)	Werri Lagoon (11)	Wooli Wooli River (-199)
9	Boambee Creek (63)	Shoalhaven River (-786)	Burrill Lake (10)	Tuross River (-190)
10	Werri Lagoon (25)	Karuah River (-776)	Lake Illawarra (9)	Port Stephens (-155)

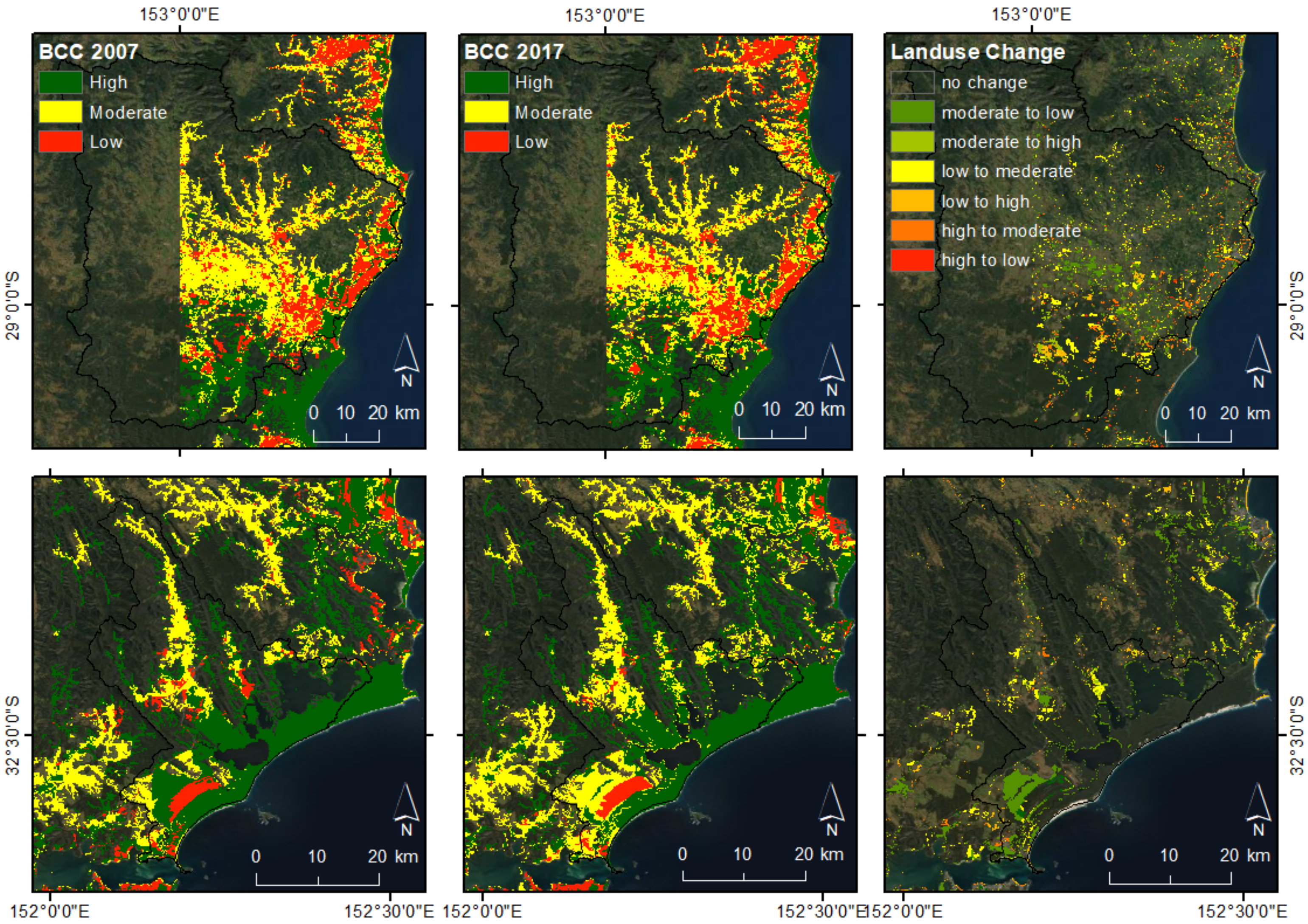


Figure 16: BCC in 2007 and 2017, and change in BCC between 2007 and 2017 for a) the Richmond River and b) Myall Lakes. (Note: the truncation on the western boundary of Richmond catchment as described in Figure 3c section 2.2)

4 Discussion

4.1 *Geomorphology as a control on blue carbon*

There is increasing awareness of intertidal position (Cacho et al., 2021), sediment character (Kelleway et al., 2016; Gorham et al., 2021) and local scale geomorphology (van Ardenne et al., 2018) as controls on coastal blue carbon storage. Outcomes from local-scale analyses have become the foundation upon which spatial frameworks for projecting blue carbon services have been developed (Rogers et al., 2019b). Additionally, landscape scale (Ewers Lewis et al., 2020), national (Cameron et al., 2021) and global-scale analyses (Rovai et al., 2018; Twilley et al., 2018) now confirm that coastal blue carbon is strongly related to estuarine geomorphology.

Using the framework of Rogers et al. (2019b), this study demonstrated that blue carbon services, indicated by BCI, are proportional to catchment area on both the north coast and south coast of NSW, and controlled by landscape geomorphology. Relationships between BCI and catchment area was improved when accounting for estuary type and the maturity. Moreover, we found that the relationship between BCI and catchment area was best predicted based on an exponential model on the north coast and a linear model on the south coast of NSW. This variation in model structure largely arises from the variation in scale of the coastal floodplains and catchments on the NSW north and south coasts. This variation arises because the western boundary of the coastal floodplain is demarcated along eastern Australia by the eastern slopes of The Great Dividing Range, and these slopes are located at a greater distance from the coastline on the NSW north coast than the south coast. Additionally, the low gradient of the continental shelf north of Newcastle provides ample lateral space for shoreline progradation and the development of broad coastal floodplains once sea-level stabilised approximately 7000 years ago (Roy et al., 1980; Roy et al., 2001). The broad coastal floodplains of the north coast contrast the south coast where the floodplain is narrow and catchments are truncated. Large estuaries within NSW provide sufficient storage and preservation of fossil blue carbon, and supports the addition of contemporary blue carbon from mangrove forests and saltmarshes. The enhanced ability for contemporary blue carbon addition along the NSW north coast is confirmed by state-wide mangrove and saltmarsh mapping, which indicates that the north coast supports 8500 ha of mangrove and 4910 ha of saltmarsh habitats, whilst the South Coast supports 1624 ha of mangrove and 1260 ha of saltmarsh (extracted from NSW Estuarine Macrophytes mapping).

Extensive coastal floodplains are also ideal for intensive cropping and grazing due to the ready access to water resources from large rivers, high coastal rainfall, and low topographic slopes. The conversion of blue carbon habitats and associated carbon storage to agricultural lands has been facilitated by wetland drainage, flood mitigation controls and tidal impediments, and these activities are markedly more extensive on the north coast of NSW where the coastal floodplain is broad and engineered structures separate larger areas from tidal exchange. The outcome of this is that the compatibility of land-use with blue carbon is also proportional to catchment area. In many instances, land-use activities that are incompatible with blue carbon can only occur due to the presence of engineered structures that serve as tidal barriers. The effect of land-use and land-cover change on blue carbon is well established, with reports of substantial declines in biomass and soil carbon stocks (Sasmito et al., 2019). Management decisions that facilitate restoration of blue carbon ecosystems, achieved either by: i) removal or management of tidal barriers; and ii) land-use change to activities compatible with blue carbon will achieve optimal blue carbon outcomes.

4.2 *Influence of barriers and opportunities for improving blue carbon services*

Regeneration efforts (i.e. restoration, rehabilitation and afforestation) can effectively improve biomass carbon stocks and re-establish soil carbon stocks (Sasmito et al. 2019). It is for this reason that the reintroduction of tidal flow to facilitate establishment of mangroves and tidal marshes is regarded as a priority activity that could be undertaken to generate ACCUs within the ERF (Kelleway et al., 2017a). This study focussed on identifying land located in watersheds upstream of tidal barriers that could be regarded as priority areas for tidal reintroduction. Due to the occurrence of broad coastal floodplains and associated greater prevalence of tidal barriers on the north coast, opportunities for reintroduction of tides above tidal barriers are particularly prevalent on the north coast. More specifically, approximately 5153 ha with high BCP are located upstream of tidal barriers on the North Coast and 919 ha were located on the South Coast.

Tidal reintroduction and reinstatement of higher water tables has already commenced in some watersheds of the NSW North Coast and notable examples include partial restorations at Hexham and Tomago Swamps on the Hunter River, Big Swamp on the Manning River, and Yarrahapini Wetland on the Macleay River (Rogers et al., 2015). The benefits of these activities not only include blue carbon services, but also an improvement in water quality associated with the reinstatement of a higher water tables and tidal exchange to acid sulfate soils, inhibiting the activation of potential acid sulfate soils and reducing the frequency and intensity of black water events. Based on the extent of high BCP area within watersheds above tidal barriers blue carbon is likely to be a particularly significant factor for barrier management decision making at: Belmore River (1240 ha above barrier); Tuckean Broadwater (1199 ha); Clybucca Creek (866 ha); Crookhaven Creek (587 ha) and Sportsmans Creek (556 ha).

4.3 Influence of land-use change and opportunities for blue carbon restoration

Due to the availability of time-series land-use mapping, consideration was also given to the influence of land-use change on blue carbon opportunities. Of concern was the increase in land-use that is incompatible with blue carbon. For example, conversion of 17 405 ha of tree and shrub cover to grazing land-use has resulted in a significant decrease in high BCC areas to moderate BCC (Table 8). Similarly, the data shows a remarkable conversion of 15 658 ha of wetland area in 2007 to grazing in 2017; although some of this may be an outcome of the dual use of wetlands for grazing and water supply to cattle and potentially different categorisations by map developers. Evidently, there remains significant opportunities to halt the existing trajectory of land-use conversion away from activities that are highly compatible with blue carbon storage, preservation and generation to intensive land-use activities that have the capacity to limit storage, generation and preservation of carbon.

Land-use changes that improve conservation of blue carbon can be achieved by increasing coastal wetland reserves, and this is likely to be simpler on publicly owned land (Bell-James and Lovelock, 2019b). However, achieving optimal blue carbon services and co-benefits not only requires consideration of tenure and land-use, but may also require interventions to ensure restoration of hydrological regimes, delivery of ecosystem services and adaptations to sea-level rise (Sadat-Noori et al., 2021). This is because, even following land-use change to improve conservation of blue carbon, past-agricultural land-use can remain imprinted on coastal wetlands for decades or centuries, with evidence of past drainage, structures and fencing retained in, and sometimes continuing to degrade, post-agricultural landscapes (Williams and Watford, 1997; MacDonald et al., 2010). These impacts are amplified by changes to biodiversity and soil biogeochemistry that can arise from decades of grazing, cropping and drainage, such as acid sulfate soils impacts including autocompaction of ground surface elevations (Johnston et al., 2003; Johnston et al., 2016). The imprint of past agricultural activities such as drainage ditches may generally be regarded as ‘minor’ and relatively inert in other landscapes, and allowing them to slowly infill with sediments remains the preferred strategy. However, within the intertidal zone, former drains and even relatively minor features such as mosquito runnels can become a conduit increased tidal flows and for supply of mangrove propagules into saltmarsh and alter the ecological character of wetlands for decades (Breitfuss et al., 2003). In some instances, where consideration of the potential impacts of tidal inundation on adjacent land-use are essential, or where acid sulfate soils have been activated, interventions to restore hydrological regimes may be substantial. Interventions can include blocking drains to raise ground water levels and sustain a lense of fresh groundwater. The implementation of ‘smart’ flood gates to manage tidal regimes may also be required, as has occurred in wetland restoration projects across the Hunter River (Sadat-Noori et al., 2021). To achieve the best delivery of blue carbon services and co-benefits, consideration should be given to both land-use change and restoration of natural hydrological regimes.

Policy and legislation in Australia (Rogers et al., 2016; Rog and Cook, 2017), and particularly NSW, now affords considerable protection to coastal wetlands from any changes to drainage or extent and have been effective in halting the trajectory of decline in wetland extent that occurred until the 1980s. However, this policy and legislation may not be effective at halting the incremental conversion of adjacent freshwater and brackish wetlands that may be hotspots of fossil blue carbon. This is evident from the ongoing generation of acid sulfate soils, whose activation arises from pyrite oxidation following drainage of carbon stores (Rosicky et al., 2004). Additionally, it will not be effective in protecting fossil blue carbon that is preserved in substrates that may no longer support contemporary mangrove forests and saltmarshes, or landward zones adjacent to contemporary blue carbon ecosystems that may become important retreat pathways as coastal wetlands respond to sea-level rise. In the absence of robust legislation that accommodates and protects coastal wetland retreat pathways as they respond to sea-level rise (Rogers et al., 2016), this pattern of land-use conversion may continue.

As land-use change may influence Australian carbon accounts and reporting to the UNFCCC, forethought should be given to any land-use changes that promote degradation of fossil blue carbon or inhibit the retreat of coastal wetlands with sea-level rise. While it is anticipated that Australia's efforts at carbon abatement and reporting obligations to UNFCCC will slow the ongoing loss of biomass in native vegetation and fossil blue carbon within substrates; rates of agricultural clearing in NSW imply otherwise (Heagney et al., 2021). The introduction of a blue carbon methodology within the ERF and the possibility to earn and sell ACCUs may provide the necessary motivation to halt the trajectory of agricultural clearance and increase the trajectory of reintroduction of tides to coastal landscapes and coastal wetland restoration.

4.4 Prioritising land for blue carbon restoration.

The anticipated approval of a blue carbon methodology within the ERF has focussed attention on prioritising land for tidal reintroduction, particularly as this activity is likely to achieve a rapid increase in blue carbon services. The method demonstrated in this study can be used to establish priority areas beyond instream barriers, and this analysis places NSW in a favourable position to propose projects within the ERF. In particular, high BCP was identified upstream of in-stream barriers at Belmore Swamp, Seven Oaks Drain and Swan Pool on the Macleay River; Tuckean Swamp on the Richmond River; Everlasting Swamp, Coldstream River, Alumy Creek and Poverty Creek on the Clarence River; and Crookhaven River and Culburra Road floodgate on the Shoalhaven River (Table 6); and these locations will serve as priority areas for further investigation of the feasibility of tidal reintroduction using the ERF methodology. The method presented in this study focussed on instream barriers and does not explicitly consider opportunities that may arise by managing levees to reintroduce tidal exchange. Further analyses that consider hydrological modification caused by levees may well highlight additional priority areas for further investigation. For example, tidal reintroduction beyond levees has already commenced at Hunter National Park to facilitate creation of shorebird and waterbird habitat, and the feasibility of an ERF project should also be investigated.

Bell-James and Lovelock (2019b) emphasise that difficulties can arise when managing barriers for tidal reintroduction, particularly when tenure is complex and public-private ownership arrangements are required. This is especially the case when ownership of the intertidal zone is complex (Rog and Cook, 2017; Bell-James and Lovelock, 2019a); hence, implementation of tidal restoration projects are likely to be expedited when the land targeted for restoration is wholly within public ownership and managed either by local, state or federal government. However, land tenure should not preclude coastal wetland restoration as it is anticipated that the ERF will incentivise land managers to consider tidal reintroduction for blue carbon services (Kelleway et al., 2017b; Macreadie et al., 2017a; Kelleway et al., 2020), and necessary approvals could be sought to facilitate restoration (Bell-James and Lovelock, 2019b). Additionally, the sale of ACCUs will offset some lost opportunity costs that may arise from converting agricultural land to blue carbon ecosystems through tidal reintroduction. As sea-level rise continues, blue carbon restoration opportunities may become the most viable land-use option for parts of the low-lying coastal floodplains.

Land above an in-stream barrier that could provide high blue carbon services and co-benefits, as identified in this study, represent priority areas for tidal reintroduction and generation of ACCUs within the ERF. This may provide sufficient incentive to facilitate the conversion of very marginal agricultural land to coastal wetland through the reintroduction of tides, particularly where approval processes are streamlined and success is facilitated (Bell-James and Lovelock, 2019b). However, where agricultural productivity continues but constraints are expected to increase with sea-level rise, other factors may make coastal wetland restoration increasingly favourable. In some cases, particularly when in-stream barriers were constructed decades ago, tidal barriers may either be failing due to ongoing degradation (e.g. concrete cancer), or may no longer meet design constraints to deliver their intended objective of holding back the tide and draining coastal landscapes. Additionally, ongoing soil diagenesis, organic matter decomposition and soil shrinkage associated with drainage of coastal landscapes can lead to significant loss of substrate elevations (Rosicky et al., 2004), sometimes to the extent where saline intrusion through substrates now reaches at or near the surface resulting in acid sulfate soil scald formation (Rosicky et al., 2004). The ingress of saline waters beyond tidal barriers is already evident in many locations by the occurrence of saltmarsh in depressions and along abandoned palaeochannels (*pers. Obs*.). In more instances, because ground surface has lowered and sea level has increased, in-stream barriers may not be able to deliver on their initial designed primary purpose of flood mitigation, instead they behave counter to this objective, at times, slowing drainage of freshwater from catchments and leading to ponded pastures, or trapping floodwaters and amplifying flooding impacts. The disservices associated with ponded pastures are well known including increased emissions of methane (Kroeger et al., 2017) and other greenhouse gases (Dalal et al., 2008). With the radiative forcing of methane in the atmosphere being 25-100 times greater than carbon dioxide, the generation of ponded pastures is contrary to national efforts to mitigate climate change (Kroeger et al., 2017).

When the efficacy of tidal barriers is becoming limited, land managers are left with option to: i) seek approval to retro-fit or re-engineer barriers, though inundation impacts will continue to increase with sea-level rise and further ingress of saline water into drained landscapes; ii) do nothing and accept that tides will increasingly over-top barriers and agricultural land-use may become less viable due to the trapping of flood and tidal waters; or iii) seek approval to remove tidal barriers, reintroduce tides and restore a natural hydrological regime. Whilst many existing barriers were established prior to the need for approvals (Creighton et al., 2015), changes to existing barriers or the construction of new ‘improved’ barriers now require approvals. This approval process, and the cost of works, may provide the opportunity for asset owners, land managers and the broader community-when the structure is owned by a public authority-to assess the services and disservices associated with tidal barriers in a site specific and informed way. In some situations ERF opportunities may become increasingly appealing. Such considerations are anticipated to become a feature of accountable asset management required by public authorities that own and manage drainage and floodgate infrastructure affected by sea-level rise. Furthermore, a delayed decision, or the ‘do nothing’ option, will not prevent the inevitable failure of barriers to hold back the tide, but may limit access to ERF opportunities as registration of an ‘activity’ was not undertaken prior to restoration occurring. Crucially, prompt decisions to remove barriers or manage them for reintroduction of tides will increasingly become the most prudent option for land managers.

Sea-level rise will also impose decisions to manage tidal barriers differently. Indeed, many areas beyond tidal barriers are already within the range of the intertidal zone and could support blue carbon ecosystems. Whilst this analysis did not explicitly consider land-use planning decisions that would facilitate coastal wetland retreat with sea-level rise, many tidal barriers have not been designed to meet anticipated increases in tidal planes associated with sea-level rise. With global mean sea level increasing by 3.6 mm y^{-1} between 2006 – 2015, and median sea level projected to increase by 0.84 m by 2100 (0.61 – 1.10 m likely range, relative to 1986 – 2005 levels under RCP8.5 scenario) (Oppenheimer et al., 2019), the coastal floodplains of both northern and southern NSW will become increasingly vulnerable to inundation. It is probable that existing tidal barriers may be overtopped, and tidal barriers will no longer hold back the tide, but inhibit drainage of tidal and flood waters, resulting in the development of ponded pastures and associated disservices.

Analyses that incorporate projections of tidal planes with sea-level rise will improve capacity to identify priority areas beyond tidal barriers that will become increasingly inundated. Here we estimate that low-lying land beyond barriers with elevations < 2 m AHD will become progressively less viable for cropping and agriculture (based on RCP 8.5 sea-level rise projection of ~1 m and 2 m tide range, centred around 0 m AHD). Given considerable evidence of the decline in ecosystem services and increases in ecosystem disservices with ponded pastures (Bell-James and Lovelock, 2019a), and potential reduction in agricultural productivity with sea-level rise (Park et al., 2008; Howden and Crimp, 2011), decisions to manage tidal barriers differently will be increasingly appealing as sea-level rise accelerates. Opportunities for generating ACCUs within the ERF are substantial in these circumstances as both reintroduction of tides, and land-use planning for sea-level rise, through the establishment of retreat pathways, are regarded to be suitable activities within the ERF framework (Kelleway et al., 2017b). These activities will also deliver on a suite of ecosystem services as coastal wetlands are restored, such as inhibiting methanogenic processes (Poffenbarger et al., 2011), improving trophic food web provision, fish passage and habitat (Rogers et al., 2015), coastal and shoreline protection, nutrient cycling, reduction in blackwater events and improved water quality (Duarte et al., 2013).

4.5 Recommendations to blue carbon opportunities in NSW

Due to aging of existing structures that serve as tidal barriers and the effects of accelerating sea-level rise on existing land-use, land managers will increasingly be required to make decisions about both existing tidal barriers and the engineering of new tidal barriers. Despite the emerging risks that increasing tidal inundation places on existing land-use, considerable opportunities are available to improve land productivity and contribute to climate change mitigation; however, this will require a paradigm shift in coastal floodplain management from one that promotes ‘holding the tide back’ to one that facilitates tidal inundation. Critically, the incentives associated with facilitating tidal inundation requires timely decisions to ensure activities that facilitate reintroduction of tides or adaptation of coastal wetlands to sea-level rise are registered within the ERF and implemented in advance of tidal reintroduction or adaptation to sea-level rise. More specifically, if an aging in-stream barrier fails prior to project registration and coastal wetland restoration commences prior to implementation of activities, the opportunity for the land manager, or broader community to benefit financially under the ERF may not be achieved. Additionally, opportunities provided by the ERF may motivate stakeholders to reinstate tidal exchange sooner and therefore, improve the capacity of land to adapt to sea-level rise prior to significant acceleration in sea-level rise. To fully-realise these opportunities and ensure that NSW is well placed to make timely decisions, we recommend the following:

i) *Auditing the location and condition of all tidal barriers in NSW*. With more than 4200 in-stream structures impeding tidal flows in coastal rivers and streams of NSW, there are tremendous opportunities for managing barriers differently. To prioritise opportunities requires more information about the precise location, ownership, land tenure, structure, condition and height of tidal barriers. An audit of tidal barriers, focussing initially on the most significant barriers, will provide decision makers with the essential information to prioritise opportunities and approve activities for reintroduction of tides. This audit will identify aging structures that no longer meet design objectives, and for which a decision regarding reengineering or removal should be made in a timely manner and with consideration given to the provision of blue carbon services and other co-benefits.

ii) *Quantifying the projected effects of sea-level rise on tidal planes*. Prioritising land above or below tidal barriers that will have tidal reintroduction imposed by sea-level rise requires consideration of future coastal wetland retreat pathways. A range of techniques can be used to identify future retreat pathways. These include relatively simple indicator techniques (Rogers and Woodroffe, 2016) and simple bath-tub modelling such as that undertaken by Commonwealth of Australia in their assessment of climate change risks to Australia's coast (DCC, 2009). Alternatively, more sophisticated approaches could be used, such as projections of tidal planes (Hanslow et al., 2018), geomorphological modelling (Rogers et al., 2013; Mogensen and Rogers, 2018), or hydrodynamic modelling (Rodríguez et al., 2017; Kumbier et al., 2018). Relatively simple bathtub modelling can be used to provide an indication of the likely upper limit of coastal wetland distribution, whilst integration with tidal plane analyses (Hughes et al. in press) may increase confidence in possible future retreat pathways, and can be used to identify retreat pathways where decisions can be made now to improve blue carbon futures.

iii) *Assessing the efficacy of existing barriers and their drainage units under different sea-level rise scenarios*. As many structures that impede tides are engineered based on past environmental conditions, it is anticipated that their ability to drain landscapes at the designed rate will diminish. This is because increased sea levels will result in fewer occasions when low tides are below the invert of the floodgate valve, a position when the floodgate outlet is totally unimpeded by estuary water levels. Often described as 'losing the low tides' and it is considered to be one of the fundamental constraints on drainage from barriers. It is also anticipated that as sea-level rise accelerates, higher tides will intrude through sand seams and macropores into landscapes previously protected by floodgate and levee infrastructure. Concurrently, the efficacy of floodgates and levees in holding back the highest tide will be exhausted once tidal planes over-top the height of in-stream structures. Integrating information about blue carbon potential with projections of the effects of sea-level rise on tidal planes, and detailed information regarding the condition and dimension of in-stream structures, will provide the capacity to identify those structures where tides will constrain operation or over-top under different sea-level rise scenarios, and when this effect is likely to occur. This information will be crucial for prioritising management of barriers in advance of sea-level rise effects occurring.

iv) *Developing decision support tools for evaluating economic and environmental costs and benefits of tidal barrier decisions*. Whilst the ERF provides the mechanism to apply an economic value to environmental benefits provided by coastal wetlands, namely by providing a market for blue carbon storage and sequestration that can be sold-on, it does not provide the basis for adequately incorporating this into decisions regarding the ongoing management of tidal barriers, particularly where a change in land-use is incurred. Assessments of agricultural financial impact coupled with the public environmental benefit associated with land-use change are rare, but do exist (see for example Beardmore et al., 2019). Tools that facilitate the adequate and fair assessment of costs and benefits associated with change in land-use, design and construction of barriers, and provision of blue carbon services and other co-benefits, will improve decision-making.

v) *Establishing policy for approving upgrades of existing or construction of new tidal barriers that accounts for blue carbon and other co-benefits*. An increase in requests to re-engineer existing structures or construct new structures is likely as structures age and anticipated sea-level rise accelerates. Equipping decision makers with a decision-making framework will ensure opportunities to mitigate climate change are realised. In NSW, the *State Environmental Planning Policy (Coastal Management)* (2019) (CM SEPP) provides a useful foundation. It presents a management objective for the coastal zone within which it maps four coastal management areas. The CM SEPP specific assessment criteria and development controls for those management areas that consent authorities must consider when assessing proposals. Decisions are also, in part, informed by the document *Policy and guidelines for fish habitat conservation and management (2013)* (Fairfull, 2013). This document largely focuses on maintaining fish passage via the design and construction of in-stream structures and the rehabilitation of barriers to fish passage. Whilst effective in meeting these objectives, this document does not provide guidance that will facilitate decisions that improve or restore blue carbon services, and in doing so, does not provide the framework for decisions that provide both fish passage and blue carbon services, and may become a barrier to achieving a payment for ecosystem services from the ERF. Furthermore, such decision making needs to consider impacts on vegetation communities, including threatened ecological communities that may have developed in response to hydrological changes caused by installation of the barrier, and which may be subsequently inundated when reintroduction of tides occurs. In NSW several of the determinations for these endangered ecological communities note a dynamic hydrological relationship between freshwater wetlands and estuaries and that "Proposals for the restoration of natural hydrological regimes and for the rehabilitation of acid sulfate soils may also result in changes to the distribution and composition of floodplain communities." These determinations also indicate that "Co-ordinated planning and management approaches across whole catchments will be required to address and resolve priorities between different management objectives."

5 Conclusions

The need to mitigate and adapt to climate change has focussed research and policy attention on nature based solutions that leverage ecosystem services. Blue carbon ecosystems provide a suite of ecosystem services that meet objectives to mitigate climate change by sequestering and storing carbon and adapt to climate change by offering shoreline protection from erosional forces of storms and adaptation to sea-level rise by the accumulation of both mineral and organic sediments. However, to fully leverage this capacity requires a paradigm shift in the management of coastal floodplains away from coastal wetland drainage to facilitate floodplain land-use for grazing and cropping activities towards the implementation of more natural hydrological regimes. This can be achieved by reducing drainage and reinstating tidal flows to facilitate coastal wetland restoration, and in doing so, carbon storage and sequestration services will increase, resilience to sea-level rise may improve and a suite of co-benefits will be provided. This paradigm shift will also ameliorate the disservices that are legacies of floodplain drainage, such as acid sulfate soil impacts, black water discharges, reduction in fish passage and declines in wildlife habitat. The Commonwealth Government of Australia are on the precipice of making a blue carbon method under the ERF, which leverages the capacity of coastal wetlands to sequester carbon. This scheme, and the increasing constraints being caused by aging in-stream barriers and sea-level rise, may provide the impetus for this paradigm shift.

This study prioritises watersheds above tidal barriers that are ideal locations for carbon offsetting within the ERF using the blue carbon methodology. Significant opportunities on the coastal floodplains of northern NSW are available for managing tidal barriers differently, reintroducing tides and restoring floodplains to natural habitats vegetated with blue carbon ecosystems (mangrove and saltmarsh). The Commonwealth of Australia is seeking to increase carbon stocks and improve reporting to UNFCCC, and the imminent development of a methodology to support payment for blue carbon restoration and management (Kelleway et al., 2020) will further incentivise the conversion of degraded coastal habitats to high priority blue carbon areas. Critically, the incentives associated with facilitating tidal inundation requires timely decisions to ensure activities that facilitate reintroduction of tides or adaptation of coastal wetlands to sea-level rise are registered within the ERF and implemented in advance of tidal reintroduction or adaptation to sea-level rise. To fully-realise these opportunities and ensure that NSW is well placed to make timely decisions, we recommend the following:

- Auditing the location and condition of all tidal barriers in NSW;
- Quantifying the projected effects of sea-level rise on tidal planes;
- Assessing the efficacy of existing barriers under different sea-level rise scenarios;
- Developing decision support tools for evaluating economic and environmental costs and benefits of tidal barrier decisions; and
- Establishing policy that requires an account of blue carbon and other co-benefits that would not be realised when considering approving upgrades to existing, or construction of new, tidal barriers.

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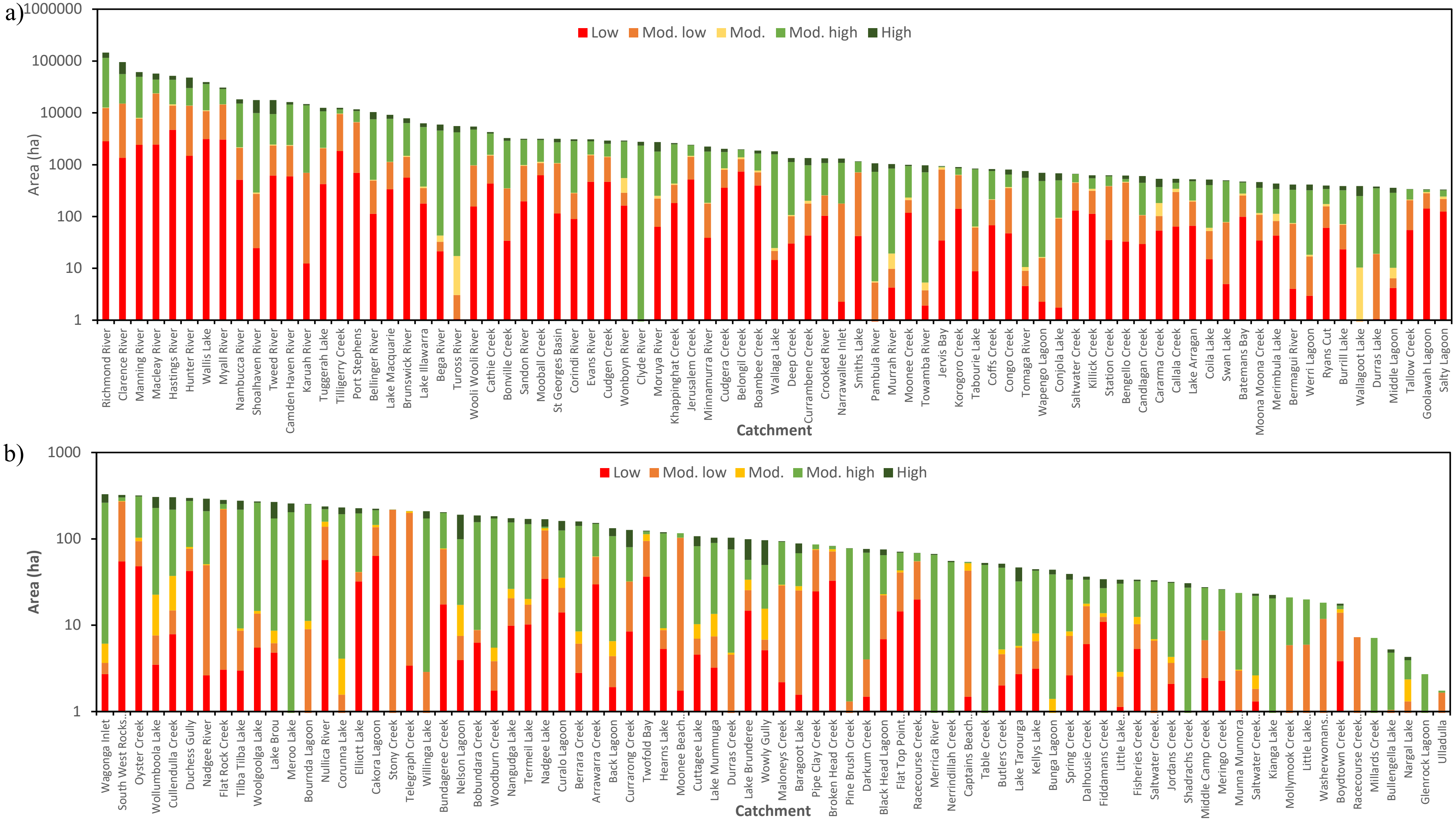
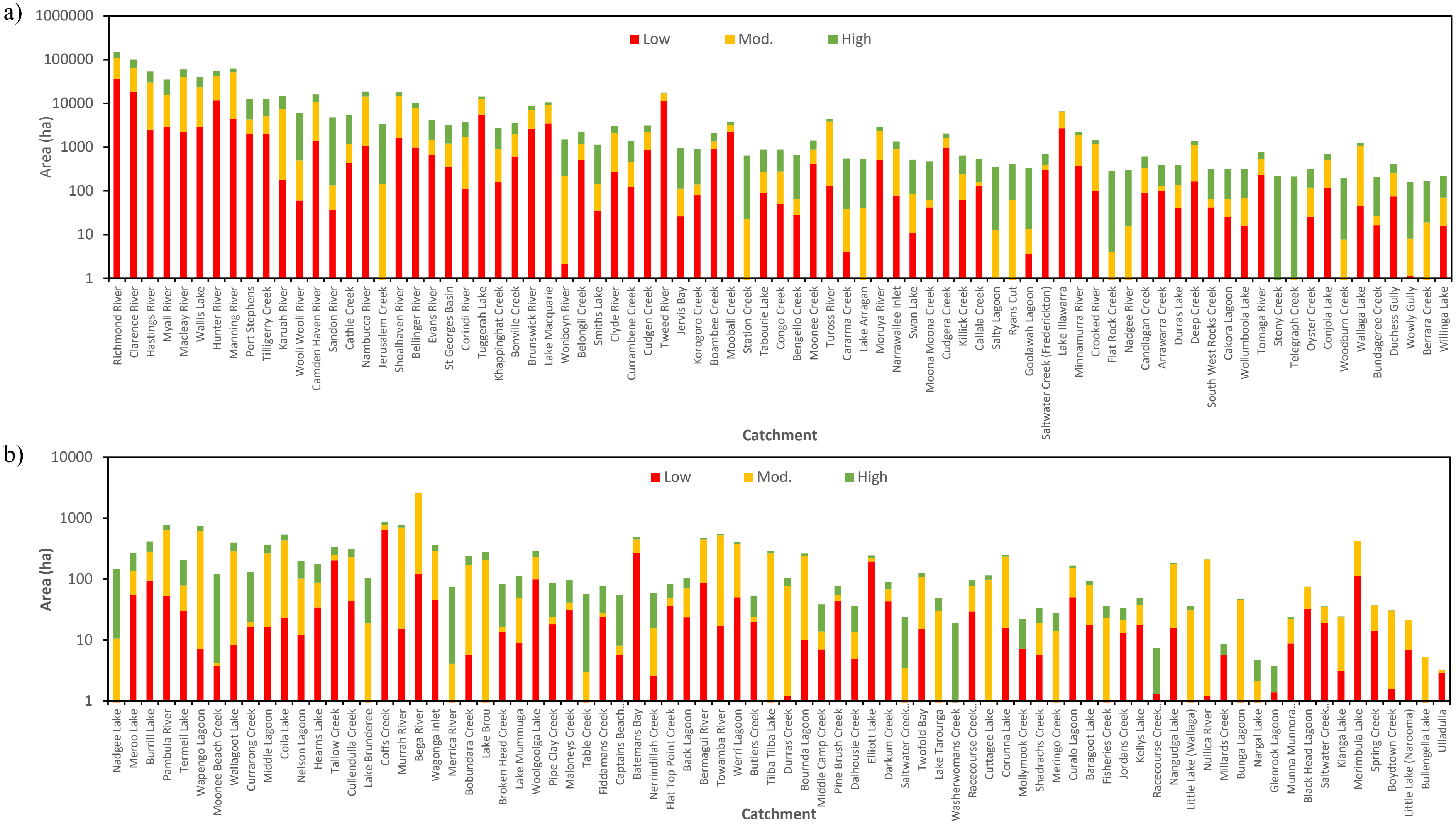
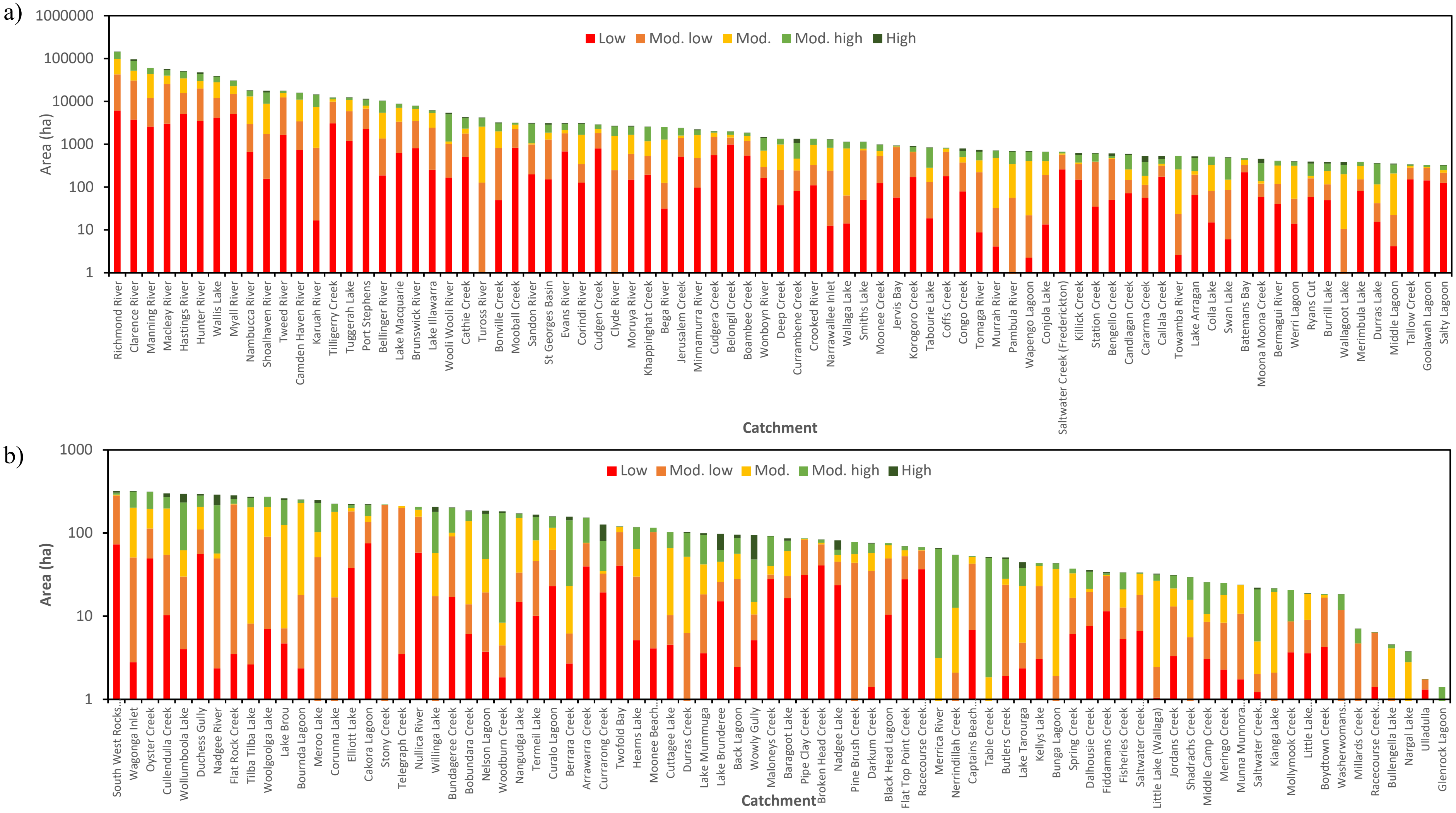
7 Supplementary Figures



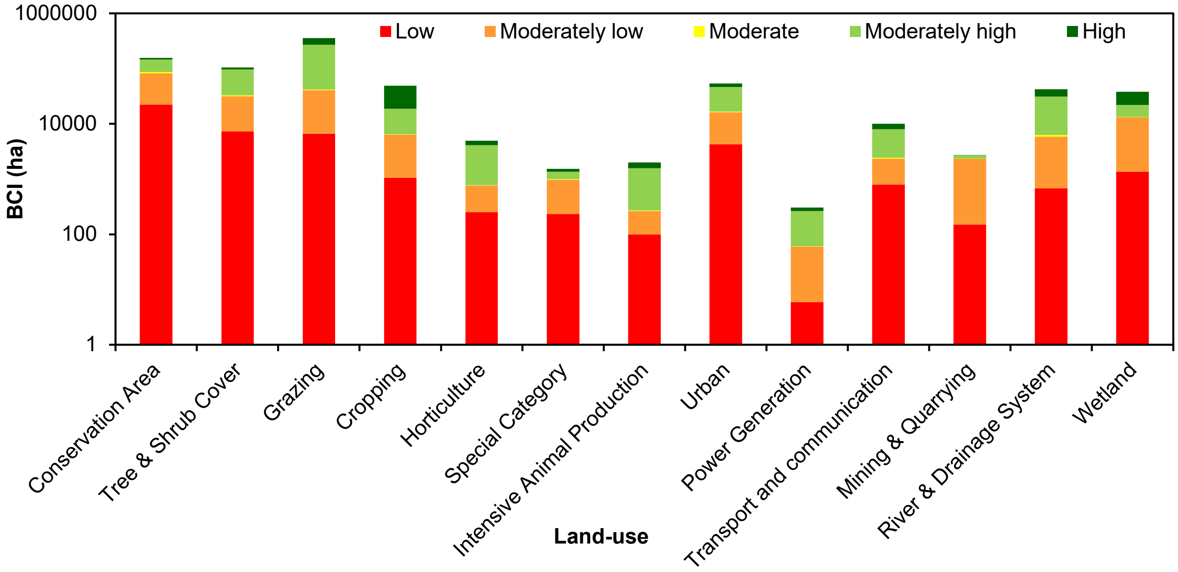
Supplementary Figure 1: BCI area (hectares) of low, moderately low, moderate, moderately high and high value within catchments. Areas have been ranked from largest in panel a) to smallest in panel b).



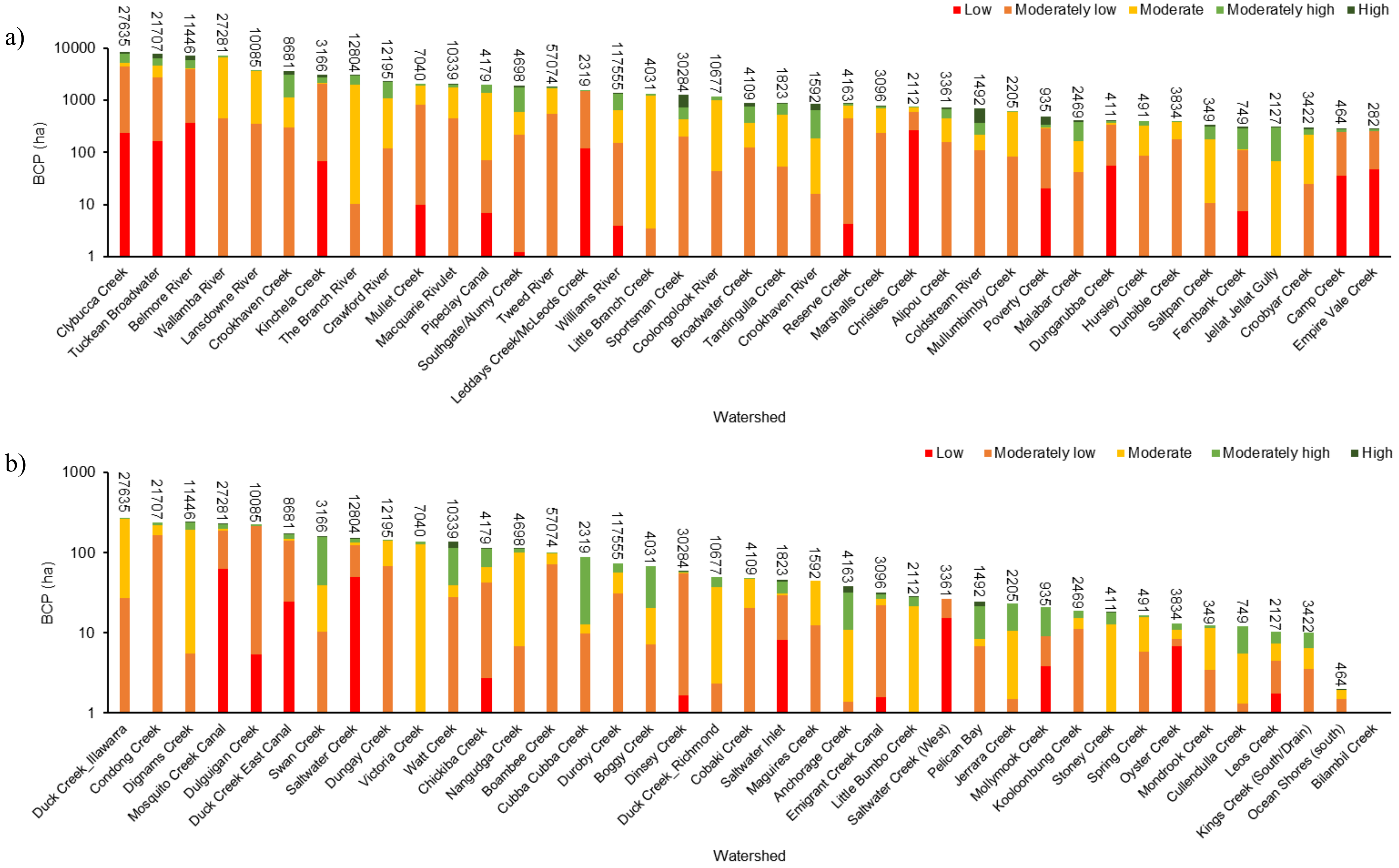
Supplementary Figure 2: BCC area (hectares) of low, moderate, and high value within catchments. Areas have been ranked from largest in panel a) to smallest in panel b).



Supplementary Figure 3: BCP area (hectares) of low, moderate, and high value within catchments. Areas have been ranked from largest in panel a) to smallest in panel b).



Supplementary Figure 4: Coincidence of BCI values and land-use across the study area. The greatest extent of total BCI coincided with grazing and conservation areas, whilst cropping had the greatest extent of high BCI area.



Supplementary Figure 5: Extent of BCP (in hectares) within watersheds located above a tidal barrier. Areas have been ranked from largest in panel a) to smallest in panel b).

8 Supplementary Tables

Supplementary Table 1: Tributaries (rivers and creeks) in which barriers were identified to have significant influence on tidal exchange. * as copied from MHL (2012).

Tributary	Catchment	Coordinates		Comment*
		X	Y	
Alipou Creek	Clarence River	495272	6714838	Earth wall (levee bank) 200m upstream from Clarence River
Anchorage Creek	Moruya River	239283	6021736	
Belmore River	Macleay River	498897	6559152	Heavy reed growth stops tide here - 1.7km upstream from Seale Road
Bilambil Creek	Tweed River	545535	6877533	At Hogans Bridge on road to Upper Duroby
Boambee Creek	Boambee Creek	506730	6643998	140m upstream from bridge on Lindsays Road
Boggy Creek	Bellinger River	501978	6630518	Tide would get to this vicinity 50m downstream from corner of South Arm Road and Pacific Highway
Broadwater Creek	Clarence River	509753	6744785	Bund wall across creek, 1.8km downstream from bridge
Camp Creek	Clarence River	518524	6740234	Floodgates 5m downstream from bridge
Chickiba Creek	Richmond River	557376	6809624	Tidal to this vicinity, 2.4km upstream from North Creek
Christies Creek	Cudgera Creek	553978	6860978	200m upstream from Kanes Road
Clybucca Creek	Macleay River	497031	6576440	Floodgates at this point, 1.6km downstream from Pacific Highway, any leakage would disperse into network of creeks and drains above floodgates (Lot 6322 DP 790009 Menarcobrinni Floodgate)
Cobaki Creek	Tweed River	545612	6880759	75m downstream from road bridge
Coldstream River	Clarence River	508593	6714212	At floodgates 0.6km upstream from The Forks
Condong Creek	Tweed River	541826	6867069	Fully tidal creek connected back to Tweed River via Johnsons Creek
Coolongolook River	Wallis Lake	436630	6433801	At causeway at Locketts Crossing
Crawford River	Myall Lakes	424067	6412766	At tidal barrage, 75m upstream from Myall River (Lot 2, DP 544774)
Croobyar Creek	Narrawallee Inlet	267990	6091613	Downstream side of weir at Avonlea farm
Crookhaven Creek	Crookhaven River	290606	6136840	Downstream side of floodgates
Crookhaven River	Crookhaven River	289186	6131407	Downstream side of floodgates
Cubba Cubba Creek	Manning River	450860	6468498	Earth embankment 700m downstream from old Pacific Highway (Lot 300, DP 1258073)
Cullendulla Creek	Cullendulla Creek	247616	6047910	Saltmarsh in this vicinity, 3.1km upstream from Batemans Bay

Tributary	Catchment	Coordinates		Comment*
		X	Y	
Dignams Creek	Wallaga Lake	231060	5971790	Downstream side of weir
Dinsey Creek	Tweed River	544722	6869853	Floodgate
Duck Creek	Lake Illawarra	297407	6176947	Large rise at old culverts under old railway bridge, 1.9km upstream from Lake
Duck Creek	Richmond River	546675	6805988	550m upstream from bridge
Duck Creek East Canal	Richmond River	548033	6806751	
Dulguigan Creek	Tweed River	541383	6870587	Fully tidal as creek now joined to Rous River by flood channels
Dunbible Creek	Tweed River	538753	6861411	May get a short way upstream from this vicinity
Dungarubba Creek	Richmond River	538572	6791678	Probably tidal to this vicinity, 875m upstream from bridge on Lismore Road (Lot 1, DP 1161249)
Dungay Creek	Tweed River	537469	6871003	Upstream side of right bend in creek, 760m NW from Pipeclay Creek junction
Duroby Creek	Tweed River	547782	6876827	Downstream side of rock dam, 100m from Benevis Place on Naponyah Road
Emigrant Creek Canal	Richmond River	548479	6807506	Floodgate
Empire Vale Creek	Richmond River	549572	6801581	Tide now stopped by floodgates, 15m upstream from bridge on River Drive
Fernbank Creek	Hastings River	484617	6524761	Tidal to this point 900m upstream from Hastings River Drive Barrier is located west of Lot 2, DP 1140746
Hursley Creek	Hastings River	476754	6522454	At weir 300m upstream from Carecorara Inlet on Lot 4, DP 729799
Jellat Jellat Gully	Bega River	223078	5932377	Benooka Lake was tidal but now a weir 450m upstream from Russels Bridge
Jerrara Creek	Minnamurra River	300177	6164593	Rise in creek directly below eastern side of new raised freeway - creek course not as marked on map so limit may be different when construction finishes
Kinchela Creek	Macleay River	498480	6569573	680m upstream from floodgates tide stopped by reed growth
Kings Creek (South/Drain)	Brunswick River	550401	6840464	At Mullumbimby-Ewingsdale Road
Kooloonbung Creek	Hastings River	491168	6522258	Tide disperses into wetland above this point, 0.9km upstream from Lake Road
Lansdowne River	Manning River	454935	6481685	At weir near Lansdowne, 2.0km downstream from railway bridge Lot 1, DP 223410
Leddays Creek/ McLeods Creek	Tweed River	549779	6872055	No apparent leakage through floodgates at Pacific Highway
Leos Creek	Twofold Bay	220546	5889198	At causeway on road crossing

Tributary	Catchment	Coordinates		Comment*
		X	Y	
Little Branch Creek	Port Stephens	408010	6395912	At ford where The Branch Lane crosses creek Lot 211, DP 870508
Little Bumbo Creek	Tuross River	230707	6007225	175m upstream from Bumbo Creek
Macquarie Rivulet	Lake Illawarra	296283	6174793	Large rise at old weir 550m upstream from Princes Highway bridge (Lot 2, DP 533684)
Maguires Creek	Richmond River	547312	6813230	Southern end of golf course, 1km upstream from bridge
Malabar Creek	Moruya River	238718	6022695	
Marshalls Creek	Brunswick River	551760	6847112	120m upstream from Pacific Highway bridge
Mollymook Creek	Mollymook Creek	270494	6086768	Entrance usually closed but tide could get to slight rise, 750m from entrance
Mondrook Creek	Manning River	445389	6470447	Tide stopped by earth embankment (Lot 85, DP 818028)
Mosquito Creek Canal	Richmond River	554036	6805456	No apparent leakage through floodgates near Mobbs Bay
Mullet Creek	Lake Illawarra	300896	6182365	Large rise at old weir, 400m downstream from railway line
Mullumbimby Creek	Brunswick River	548066	6839694	At weir 520m upstream from Poplar Street bridge
Nangudga Creek	Nangudga Lake	242296	5985160	Downstream side of weir 100m downstream from Old South Coast Road
Ocean Shores (South)	Brunswick River	552974	6845754	Small weir 4m upstream from culverts under road going to maintenance sheds
Oyster Creek	Manning River	460370	6464299	Rises in creek then disperses into wetland 80m upstream from cow track culverts (Lot 300, DP 1258073)
Pelican Bay	Manning River	464127	6474249	Not a closed system connected back to river at this point by culvert
Pipeclay Canal	Manning River	469333	6483407	At crossing on road to Coral Ville. Major rehab site
Poverty Creek	Clarence River	516575	6740294	Some leakage through floodgates at this point but creek connects back to river via Poverty Creek drain at 513440E 6738520N, so no real tidal limit
Reserve Creek	Cudgen Creek	551701	6865664	Creek would be tidal all the way to Clothiers Creek Road
Saltpan Creek	Crookhaven River	290663	6132597	On upstream side of causeway near bend in Bournes Lane
Saltwater Creek (West)	Port Stephens	547520	6800136	Bund wall of Racecourse Swamp, 2.5km upstream from Twelve Mile Creek (Lot 1 DP 1734441)
Saltwater Inlet	Macleay River	398316	6376686	Any leakage through floodgates at this point could get a further 700m upstream
Saltwater Creek	Richmond River	503508	6576306	Floodgate

Tributary	Catchment	Coordinates		Comment*
		X	Y	
Southgate/ Alumy Creek	Clarence River	501765	6722950	Tide stopped by weir 100m from Clarence River
Sportsmans Creek	Clarence River	506257	6735297	Tide gets past barrage 3.5km upstream from Clarence River and would probably reach at least to this point, 3.7km downstream from railway bridge (Lot 1, DP 1234389)
Spring Creek	Spring Creek	302600	6162259	Large rise through culverts 900m upstream from entrance
Stoney Creek	Lake Brou	238098	5997729	250m upstream from Whittakers Creek
Swan Creek	Clarence River	496253	6717371	At floodgates 20m upstream from Clarence River
Tandingulla Creek	Shoalhaven River	285843	6143129	Floodgates at Sopers Road in good condition
The Branch River	Port Stephens	407062	6399368	Very small tide measured immediately upstream of old causeway, 800m downstream from The Branch Lane bridge
Tuckean Broadwater	Richmond River	539489	6793915	Tide in Hendersons Drain would disperse into Tuckean Swamp in this vicinity, 6.5km upstream from Bagotville Barrage
Tweed River	Tweed River	536919	6864062	Tide gets to weir, 5.3km upstream from bridge at Murwillumbah
Victoria Creek	Tilba Tilba Lake	241322	5978684	Old weir 250m downstream from bridge on road to Sunnyside farm
Wallamba River	Wallis Lake	440824	6447536	Old causeway at Clarksons Crossing, 300m upstream from Pacific Highway
Watt Creek	Nambucca River	495947	6604999	At start of new drainage works, 1.8km upstream from Nambucca River
Williams River	Hunter River	381432	6385687	Tide stopped by Seaham Weir, 500m upstream from The Jim Scott Bridge (Lot 11 DP 542642)

Supplementary Table 2: Area (ha) of low, moderate, high, and total cell scores for blue carbon storage, preservation, generation and permanency in catchments. Catchments are listed in alphabetical order.

Estuary	Catchment Area (ha)	Storage				Preservation				Generation				Permanency			
		Low	Mod.	High	Total	Low	Mod.	High	Total	Low	Mod.	High	Total	Low	Mod.	High	Total
Arrawarra Creek	1795	52	81	9	142	52	83	12	147	2	4	9	15	24	7	113	144
Back Lagoon	3175	7	111	16	133	7	122	8	136	1	14	14	29	5	6	122	133
Baragoot Lake	1316	28	43	18	89	28	35	28	91	6	8	15	29	6	24	59	89
Batemans Bay	6249	278	155	42	474	279	100	102	480	17	9	41	67	136	52	287	474
Bega River	194021	41	5297	582	5920	41	5467	440	5948	24	557	806	1388	33	404	5484	5920
Bellinger River	110849	266	7758	2044	10068	269	9737	347	10354	81	2507	335	2923	147	244	9891	10282
Belongil Creek	3068	1330	397	190	1917	1333	125	523	1981	150	10	149	309	925	332	715	1972
Bengello Creek	1633	458	111	35	604	459	146	1	606	5	35	77	116	43	0	561	604
Bermagui River	8562	74	276	64	414	74	225	167	466	23	29	64	116	6	107	300	414
Berrara Creek	3530	8	130	20	159	8	85	67	161	7	1	19	27	6	41	111	159
Black Head Lagoon	200	21	42	11	74	21	46	8	75	2	11	2	15	8	5	63	75
Boambee Creek	4948	659	878	216	1753	660	992	202	1854	94	187	117	398	505	167	1169	1841
Bobundara Creek	1389	4	149	29	182	4	179	0	184	0	29	7	36	2	0	180	182
Bonville Creek	11513	252	2623	271	3146	252	2922	74	3247	7	307	46	360	30	50	3155	3235
Bournda Lagoon	3459	11	241	2	254	11	235	11	258	1	0	6	7	3	6	245	254
Boydtown Creek	388	15	2	1	18	16	0	3	19	1	0	2	3	6	2	10	18
Broken Head Creek	117	76	4	3	83	76	0	7	83	10	0	6	15	46	5	31	83
Brunswick River	22993	1154	4877	1508	7540	1159	5641	1045	7845	207	1296	303	1805	657	794	6356	7808
Bullengella Lake	74	1	3	2	5	1	1	3	5	0	0	0	1	1	2	3	5
Bundageree Creek	1013	77	120	6	204	77	111	16	204	4	5	2	10	22	3	179	204
Bunga Lagoon	1168	1	37	6	44	1	40	4	45	1	4	2	6	1	2	41	44
Burrill Lake	6512	72	255	63	389	72	275	50	397	3	49	23	76	26	26	336	389

Estuary	Catchment Area (ha)	Storage				Preservation				Generation				Permanency			
		Low	Mod.	High	Total	Low	Mod.	High	Total	Low	Mod.	High	Total	Low	Mod.	High	Total
Butlers Creek	309	5	40	7	52	5	40	7	53	1	4	2	7	3	4	45	52
Cakora Lagoon	1269	137	32	46	215	137	0	82	219	29	0	23	51	75	78	65	218
Callala Creek	1979	341	158	33	533	342	71	121	534	30	10	123	163	127	111	295	533
Camden Haven River	62115	1425	12649	1382	15455	1413	13384	1215	16012	385	1553	803	2740	773	1003	14396	16171
Candlagan Creek	2431	107	379	116	602	107	435	63	606	13	90	69	172	36	39	528	602
Captains Beach Lagoon	319	52	1	0	54	52	2	0	54	1	0	10	11	12	0	42	54
Cararma Creek	919	182	260	91	533	182	0	356	538	86	0	241	327	159	312	61	533
Cathie Creek	11925	860	2470	248	3579	865	2062	1217	4144	180	85	397	662	389	1017	2715	4120
Clarence River	2218742	5722	57411	22980	86112	5744	81062	8651	95457	1443	30562	9149	41155	1350	7195	86753	95299
Clyde River	174046	0	2389	374	2763	0	2397	569	2966	52	246	187	485	0	315	2448	2763
Coffs Creek	2450	203	536	66	805	203	583	35	821	15	63	11	88	84	21	711	815
Coila Lake	5476	61	369	88	517	61	389	78	528	15	66	57	139	27	61	429	517
Congo Creek	4332	360	304	130	794	360	330	110	800	26	89	95	210	62	83	649	794
Conjola Lake	14581	94	460	129	683	94	366	237	697	8	84	102	193	5	128	550	683
Corindi River	14834	254	2462	345	3061	255	2486	358	3099	86	192	62	339	100	300	2684	3084
Corunna Lake	3187	4	201	26	232	4	198	39	241	4	20	22	45	4	22	206	232
Crooked River	3227	176	744	334	1254	176	794	273	1242	40	266	126	431	28	168	1058	1254
Cudgen Creek	7076	1266	894	579	2739	1266	756	863	2885	185	294	177	657	527	675	1673	2875
Cudgera Creek	6103	832	911	249	1993	833	1083	97	2013	130	235	75	440	531	71	1408	2010
Cullendulla Creek	1645	37	216	51	303	37	98	175	310	35	12	95	143	34	139	130	303
Curalo Lagoon	2904	36	108	18	161	36	93	36	165	6	10	35	51	26	30	105	161
Currambene Creek	16224	201	907	236	1344	201	749	417	1368	76	135	259	469	76	343	926	1344
Currarong Creek	1237	32	72	23	127	32	15	80	128	15	2	45	62	9	74	44	127
Cuttagee Lake	5447	10	73	24	108	10	62	41	113	6	13	16	35	9	25	74	108
Dalhousie Creek	633	9	13	6	27	9	2	26	36	3	0	4	7	8	20	8	36
Darkum Creek	617	2	63	9	74	2	63	11	76	1	5	1	8	2	8	66	75
Deep Creek	9153	73	1055	183	1311	73	1177	94	1344	21	194	41	256	42	70	1230	1343

Estuary	Catchment Area (ha)	Storage				Preservation				Generation				Permanency			
		Low	Mod.	High	Total	Low	Mod.	High	Total	Low	Mod.	High	Total	Low	Mod.	High	Total
Duchess Gully	1062	67	198	21	286	65	208	11	284	6	26	15	48	41	4	245	289
Durras Creek	594	5	87	12	103	5	20	79	104	4	0	28	32	1	43	59	103
Durras Lake	6213	19	303	55	377	19	175	195	388	20	11	17	48	1	79	297	377
Elliott Lake	1005	41	115	69	226	39	119	59	216	17	32	4	53	37	54	134	226
Evans River	7850	1329	1189	343	2860	1336	847	881	3063	131	184	182	497	539	430	2073	3042
Fiddamans Creek	156	11	14	7	32	12	21	0	33	1	7	3	11	11	0	21	32
Fisheries Creek	654	12	19	2	34	13	10	12	34	2	0	3	5	9	3	22	34
Flat Rock Creek	689	222	52	9	283	222	4	57	283	5	0	31	36	6	42	235	283
Flat Top Point Creek	259	42	24	4	70	43	22	7	71	4	1	3	8	18	7	46	71
Glenrock Lagoon	742	0	2	1	3	1	0	2	3	0	0	0	0	0	1	2	3
Goolawah Lagoon	408	262	27	11	300	262	1	71	334	20	0	20	40	176	51	107	334
Hastings River	368853	10316	32084	4990	47390	10350	35703	5516	51569	1460	5724	3368	10552	6266	2909	42205	51380
Hearns Lake	675	5	99	11	115	5	94	19	119	4	1	4	9	5	19	94	118
Hunter River	2141399	8424	24962	9874	43260	8416	34109	5293	47818	1388	13409	5672	20469	1642	4590	41478	47710
Jerusalem Creek	4864	1365	898	30	2293	1377	909	48	2333	86	26	157	269	571	45	1704	2320
Jervis Bay	15628	887	44	12	943	895	9	50	954	13	3	107	123	126	37	780	943
Jordans Creek	254	4	27	0	31	4	27	1	32	0	0	1	2	3	1	28	32
Karuah River	146630	0	13486	625	14111	0	13323	1249	14572	223	503	362	1088	0	1185	13486	14671
Kellys Lake	218	8	31	5	45	8	28	9	45	2	1	2	5	6	6	33	45
Khappinghat Creek	9192	285	2076	117	2478	280	2064	210	2553	64	109	117	290	208	174	2202	2584
Kianga Lake	767	0	16	6	22	0	13	10	23	1	0	2	3	0	8	14	22
Killick Creek	822	258	192	91	540	258	184	185	626	42	54	55	151	169	106	349	624
Korogoro Creek	979	570	152	108	829	570	10	316	896	79	1	60	140	181	263	450	894
Lake Arragan	1025	195	191	126	512	196	147	179	522	30	28	22	80	87	142	293	521
Lake Brou	4409	9	204	55	267	9	210	56	274	10	42	55	108	8	46	213	267
Lake Brunderee	593	34	58	8	99	34	21	46	101	7	3	48	58	26	43	30	99

Estuary	Catchment Area (ha)	Storage				Preservation				Generation				Permanency			
		Low	Mod.	High	Total	Low	Mod.	High	Total	Low	Mod.	High	Total	Low	Mod.	High	Total
Lake Illawarra	27427	299	5072	805	6177	300	5579	275	6154	107	849	258	1213	212	270	5748	6231
Lake Macquarie	71848	574	6776	1235	8586	581	7928	801	9309	159	1180	372	1711	350	744	8015	9110
Lake Mummuga	2741	14	74	16	103	14	64	33	110	6	7	13	26	12	19	72	103
Lake Tarourga	631	6	37	4	47	6	36	6	48	1	2	12	16	3	2	41	47
Little Lake (Narooma)	227	6	11	3	20	6	5	9	21	0	0	0	0	1	3	16	20
Little Lake (Wallaga)	251	3	26	5	34	3	24	8	35	1	2	2	5	2	6	26	34
Macleay River	1131867	5469	28324	5001	38794	5471	46151	5219	56840	811	7685	6284	14781	2833	4203	49734	56769
Maloneys Creek	820	29	49	15	94	29	11	54	94	2	0	2	4	3	18	72	94
Manning River	815922	4810	46907	7233	58949	4753	50101	5555	60409	2148	8976	4879	16003	2911	4853	53118	60882
Merimbula Lake	4350	113	272	45	430	126	250	78	454	22	31	91	145	89	63	278	430
Meringo Creek	538	9	14	4	26	9	7	12	28	1	0	0	1	3	5	19	26
Meroo Lake	2064	1	212	44	256	1	156	106	263	12	14	39	64	1	67	188	256
Merrica River	6068	1	64	2	67	1	62	6	69	0	1	2	3	1	3	64	67
Middle Camp Creek	503	6	16	5	27	8	14	8	30	1	0	0	1	2	6	19	28
Middle Lagoon	2788	10	292	55	357	10	232	120	362	8	37	36	82	9	47	301	357
Millards Creek	451	0	7	0	7	0	7	1	7				0	0	0	7	7
Minnamurra River	11919	179	1578	477	2235	173	1652	361	2186	79	410	154	643	47	319	1873	2238
Mollymook Creek	272	6	15	0	21	6	11	4	21				0	0	0	21	21
Mooball Creek	10968	1016	1556	451	3023	1021	1400	697	3118	225	120	155	500	760	568	1775	3103
Moona Moona Creek	2871	117	216	127	461	117	153	195	466	35	42	70	147	49	164	248	461
Moonee Beach Creek	348	103	13	0	116	105	13	1	120	1	0	0	1	2	0	113	116
Moonee Creek	4152	212	707	55	973	212	709	68	988	30	38	43	111	152	49	782	983
Moruya River	142982	248	1915	579	2742	249	2283	272	2804	57	514	476	1047	108	214	2420	2742
Munna Munnora Creek	363	3	19	2	24	3	13	5	21	0	0	0	0	1	2	21	24

Estuary	Catchment Area (ha)	Storage				Preservation				Generation				Permanency			
		Low	Mod.	High	Total	Low	Mod.	High	Total	Low	Mod.	High	Total	Low	Mod.	High	Total
Murrah River	19660	19	868	142	1029	19	974	45	1038	7	133	69	209	16	31	982	1029
Myall River	93393	13541	14383	1875	29799	13442	14045	2571	30058	1116	1659	1505	4279	3460	1896	25027	30382
Nadgee Lake	1491	103	33	3	139	104	5	32	141	3	1	68	72	15	30	94	139
Nadgee River	5908	51	220	21	292	51	97	148	296	11	0	84	95	5	114	174	292
Nambucca River	131157	1321	14192	1850	17363	1322	16305	590	18217	140	2402	721	3263	640	497	17058	18195
Nangudga Lake	1021	26	129	19	174	26	116	35	178	5	8	17	30	19	22	134	174
Nargal Lake	94	2	1	0	4	2	0	2	5	1	0	1	2	2	1	1	4
Narrawallee Inlet	8196	178	879	263	1320	178	978	175	1331	17	196	34	247	3	96	1221	1320
Nelson Lagoon	2834	17	156	16	190	17	83	97	197	5	6	94	106	15	81	94	190
Nerrindillah Creek	1729	0	55	0	55	0	49	8	57	0	0	2	2	0	2	54	55
Nullica River	5513	158	68	12	238	158	68	14	240	16	9	28	54	93	10	136	238
Oyster Creek	1692	88	205	10	303	88	185	44	318	10	3	14	28	65	29	224	318
Pambula River	30132	6	840	217	1063	6	1007	104	1117	7	208	126	342	0	39	1024	1063
Pine Brush Creek	735	1	76	1	78	1	76	1	78	0	1	0	1	1	0	77	78
Pipe Clay Creek	164	76	10	0	86	76	10	0	86	3	0	2	5	29	0	57	86
Port Stephens	43114	5791	4336	974	11102	5764	2782	2990	11536	949	268	1047	2263	778	2912	7988	11679
Racecourse Creek (Old Bar)	276	55	12	2	68	54	9	4	67	2	0	1	3	22	1	46	68
Racecourse Creek (Ulladulla)	367	7	0	0	7	7	0	0	8				0	0	0	7	7
Richmond River	690022	6292	110889	21621	138802	6315	131396	7498	145209	1334	24729	5443	31506	3367	5206	136290	144863
Ryans Cut	492	132	151	73	355	132	89	175	397	38	27	47	112	89	128	179	396
Saltwater Creek (Eden)	1724	3	18	2	23	3	8	13	23	1	0	2	3	3	4	17	23
Saltwater Creek (Frederickton)	1140	448	184	27	659	450	159	61	670	32	5	20	58	165	47	456	668

Estuary	Catchment Area (ha)	Storage				Preservation				Generation				Permanency			
		Low	Mod.	High	Total	Low	Mod.	High	Total	Low	Mod.	High	Total	Low	Mod.	High	Total
Saltwater Creek (Rosedale)	282	7	25	2	33	7	25	2	33	1	1	0	2	1	0	31	33
Salty Lagoon	373	205	58	31	294	207	0	119	326	45	0	46	91	172	88	64	324
Sandon River	13414	914	1986	174	3074	919	2010	192	3121	65	112	103	279	208	152	2736	3096
Shadrachs Creek	1324	1	26	4	31	1	30	1	32	0	3	0	3	0	1	30	31
Shoalhaven River	711772	288	12741	4700	17729	289	15151	2460	17900	569	3961	3860	8390	45	2233	15452	17729
Smiths Lake	3798	681	401	52	1134	680	322	137	1140	23	17	27	67	52	96	1012	1159
South West Rocks Creek	461	193	36	12	241	193	1	127	322	14	0	24	37	63	119	138	321
Spring Creek	588	8	23	8	39	8	21	8	36	1	7	2	10	4	4	31	39
St Georges Basin	35666	1071	1766	309	3146	1073	1583	532	3188	67	182	292	542	151	359	2637	3146
Station Creek	2162	386	213	23	622	387	234	3	624	5	23	6	34	45	2	575	623
Stony Creek	238	218	2	0	220	218	2	0	220				0	0	0	219	220
Swan Lake	3106	78	356	64	498	78	266	161	505	47	13	5	65	7	100	391	498
Table Creek	1735	1	49	3	53	1	44	9	54	0	0	3	3	1	5	47	53
Tabourie Lake	4763	64	718	63	845	64	634	156	855	6	27	11	44	13	45	787	845
Tallow Creek	546	205	110	17	332	205	80	54	339	9	3	8	20	68	24	247	339
Telegraph Creek	429	209	0	1	210	210	0	1	210	1	0	10	11	14	1	195	210
Termeil Lake	1462	17	134	16	167	17	95	58	171	7	3	24	34	12	36	119	167
Tilba Tilba Lake	1827	9	229	39	276	9	228	43	281	10	28	31	70	5	39	233	276
Tilligerry Creek	13522	8616	2030	1025	11671	8599	0	3791	12390	1460	0	1349	2809	2364	3589	6486	12439
Tomaga River	9371	11	540	202	753	11	400	357	768	49	84	113	246	6	262	484	753
Towamba River	102919	5	869	102	976	5	856	125	987	10	91	171	272	4	108	863	976
Tuggerah Lake	79523	1849	8950	1425	12224	1882	10313	446	12641	137	1540	359	2036	466	391	11556	12413
Tuross River	182928	16	4940	632	5589	16	5464	203	5684	18	603	802	1423	16	142	5430	5589
Tweed River	107748	1123	9533	5461	16117	1124	13252	3166	17542	768	6324	1796	8888	850	2661	13801	17312
Twofold Bay	4175	112	10	1	123	114	10	1	125	8	1	20	29	61	1	62	123

Estuary	Catchment Area (ha)	Storage				Preservation				Generation				Permanency			
		Low	Mod.	High	Total	Low	Mod.	High	Total	Low	Mod.	High	Total	Low	Mod.	High	Total
Ulladulla	39	2	0	0	2	2	0	0	2	0	0	0	0	0	0	1	2
Wagonga Inlet	10022	6	258	65	328	6	242	106	354	13	33	36	83	6	61	262	328
Wallaga Lake	27314	21	1656	139	1815	21	1657	169	1846	25	102	143	270	15	126	1674	1815
Wallagoot Lake	3051	10	328	51	389	10	246	137	394	11	29	120	161	10	122	256	389
Wallis Lake	129561	9366	25775	2774	37914	9322	25521	4042	38884	1367	2681	2106	6154	3848	3228	32139	39214
Wapengo Lagoon	7218	17	556	124	696	17	415	295	727	22	65	147	234	3	196	497	696
Washerwomans Creek	254	12	6	0	18	12	6	1	18				0	0	0	18	18
Werri Lagoon	1663	18	292	102	412	18	341	43	401	14	100	20	134	4	45	363	412
Willinga Lake	1390	3	168	39	209	3	104	106	213	9	12	26	47	0	56	153	209
Wollumboola Lake	4046	23	191	91	305	23	211	80	314	19	55	37	111	22	66	217	305
Wonboyn River	33977	550	2315	38	2904	551	2148	219	2917	100	2	359	461	516	140	2248	2904
Woodburn Creek	1356	6	173	4	183	6	167	13	186	3	2	10	16	5	12	167	183
Woolgoolga Lake	2118	6	246	10	263	6	240	25	272	2	6	4	12	6	16	248	270
Wooli Wooli River	18374	801	3887	562	5251	803	3982	638	5423	87	508	186	782	179	349	4875	5403
Wowly Gully	619	15	62	19	96	16	1	81	98	11	0	56	67	14	76	6	96

Supplementary Table 3: Area (ha) of low, moderate and high cell scores for BCI, BCC (2017) and BCP (2017) in catchments. Catchments are listed in alphabetical order.

Estuary	BCI					BCC 2017			BCP 2017				
	Low	Mod. low	Mod.	Mod. high	High	Low	Mod.	High	Low	Mod. low	Mod.	Mod. high	High
Arrawarra Creek	30	32	1	86	4	100	32	261	40	35	2	74	2
Back Lagoon	2	2	2	101	26	24	47	33	2	26	28	31	9
Baragoot Lake	2	24	3	40	21	18	63	13	16	14	31	20	6
Batemans Bay	99	153	26	173	24	267	178	47	222	108	105	34	5
Bega River	21	11	10	4529	1351	119	2433	77	31	94	1158	1238	29
Bellinger River	113	379	19	6997	2849	976	6741	2744	187	1176	4050	4687	253
Belongil Creek	734	555	101	535	54	510	693	1068	985	445	237	300	18
Bengello Creek	33	420	16	62	84	28	37	588	50	408	19	51	83
Bermagui River	4	69	2	251	89	87	358	33	41	78	200	80	9
Berrara Creek	3	3	2	132	18	0	19	147	3	3	17	119	15
Black Head Lagoon	7	15	1	42	11	32	42	1	10	39	22	5	0
Boambee Creek	397	317	56	869	229	917	433	741	545	645	389	231	54
Bobundara Creek	6	2	0	147	31	6	165	69	6	8	126	42	5
Bonville Creek	34	314	1	2551	347	615	1397	1563	50	774	1181	1062	177
Bournda Lagoon	1	8	2	239	4	10	228	27	2	16	212	21	1
Boydtown Creek	4	10	1	2	1	2	29	0	4	12	1	1	0
Broken Head Creek	33	39	5	6	1	14	3	67	41	33	4	6	1
Brunswick River	566	854	57	4898	1504	2630	4532	1485	808	2683	3122	1208	58
Bullengella Lake	1	0	0	4	0	0	5	0	1	0	3	0	0
Bundageree Creek	17	59	1	122	5	16	11	177	17	74	9	100	2
Bunga Lagoon	0	1	0	37	5	0	44	3	0	2	35	6	0
Burrill Lake	23	46	2	247	70	95	187	131	50	67	122	116	28
Butlers Creek	2	3	1	41	5	20	4	30	2	22	4	21	2
Cakora Lagoon	63	73	9	70	9	25	39	254	75	61	23	57	6
Callala Creek	64	231	46	105	87	129	32	377	174	142	33	99	81
Camden Haven River	600	1707	72	11993	1830	1374	9314	5501	740	2663	7511	4646	470
Candlagan Creek	29	76	2	338	157	92	243	280	72	73	114	307	34
Estuary	**BCI**					**BCC 2017**			**BCP 2017**				

	Low	Mod. low	Mod.	Mod. high	High	Low	Mod.	High	Low	Mod. low	Mod.	Mod. high	High
Captains Beach Lagoon	1	41	10	1	0	6	2	48	7	36	9	1	0
Cararma Creek	54	48	80	190	161	4	35	512	56	57	70	199	148
Cathie Creek	432	1074	46	2431	284	431	776	4314	507	1278	526	1746	206
Clarence River	1363	13722	82	41004	39445	18372	44813	36345	3749	26949	21034	36005	7877
Clyde River	0	0	0	2330	433	266	1830	960	0	249	1311	1059	108
Coffs Creek	68	142	5	539	68	638	137	82	179	485	123	32	2
Coila Lake	15	37	8	342	115	23	413	101	15	67	246	181	0
Congo Creek	47	307	14	273	161	50	225	610	79	294	127	185	114
Conjola Lake	2	90	3	406	183	117	392	196	13	177	209	265	6
Corindi River	90	191	7	2576	239	114	1608	2028	127	220	1303	1288	162
Corunna Lake	0	1	3	189	39	16	218	16	1	16	164	43	2
Crooked River	103	150	3	819	259	100	1097	289	110	223	632	358	4
Cudgen Creek	465	930	40	1078	398	869	1330	926	803	1028	468	563	50
Cudgera Creek	356	437	58	909	253	984	633	397	560	883	436	124	7
Cullendulla Creek	8	7	22	181	85	43	187	85	10	45	142	74	30
Curalo Lagoon	14	13	8	89	36	50	104	14	23	40	53	42	0
Currambene Creek	43	136	22	772	371	123	333	928	81	164	220	602	267
Currarong Creek	8	23	0	48	47	17	4	110	19	13	2	46	46
Cuttagee Lake	5	2	3	72	25	1	97	18	5	6	56	36	1
Dalhousie Creek	6	11	1	16	3	5	9	23	8	12	2	13	1
Darkum Creek	1	3	0	65	7	43	25	21	1	34	22	17	1
Deep Creek	30	70	6	1011	227	164	968	255	38	213	741	320	33
Duchess Gully	42	35	3	194	23	75	180	165	56	54	97	74	13
Durras Creek	0	4	0	71	28	1	75	28	1	6	46	48	3
Durras Lake	1	18	0	331	28	41	97	256	16	27	73	240	10
Elliott Lake	32	9	0	156	29	195	28	22	38	144	18	18	4
Evans River	470	1047	49	1271	264	671	766	2696	685	1119	336	821	144
Fiddamans Creek	11	2	1	13	7	24	3	50	11	19	1	1	1
Fisheries Creek	5	5	2	20	1	0	23	13	5	7	8	12	0
Flat Rock Creek	3	217	2	32	29	1	3	286	3	217	4	31	28
Estuary	**BCI**					**BCC 2017**			**BCP 2017**				

	Low	Mod. low	Mod.	Mod. high	High	Low	Mod.	High	Low	Mod. low	Mod.	Mod. high	High
Flat Top Point Creek	14	26	2	26	2	36	13	34	28	25	9	7	1
Glenrock Lagoon	0	0	0	2	0	1	0	2	0	0	0	1	0
Goolawah Lagoon	143	137	16	34	4	4	10	320	144	134	16	33	5
Hastings River	4697	9075	786	29003	8127	2530	27638	23635	5057	10754	18637	14944	2291
Hearns Lake	5	3	1	106	4	34	54	92	5	25	34	53	2
Hunter River	1485	12174	97	16272	17841	11726	29397	13136	3505	16447	9730	14376	3365
Jerusalem Creek	516	902	62	896	33	0	144	3213	513	902	185	772	31
Jervis Bay	34	769	83	30	26	26	87	850	58	795	38	38	13
Jordans Creek	2	2	1	27	1	13	8	12	3	10	8	9	1
Karuah River	12	685	0	13336	661	176	7373	7250	17	815	6486	7101	171
Kellys Lake	3	3	1	35	2	18	20	11	3	20	17	3	0
Khappinghat Creek	181	228	24	2034	138	156	769	1781	195	335	639	1324	84
Kianga Lake	0	0	0	20	2	3	21	1	0	2	17	2	0
Killick Creek	113	200	29	204	80	61	183	389	149	194	30	187	66
Korogoro Creek	141	481	14	213	48	80	59	766	172	475	28	181	41
Lake Arragan	66	129	9	276	41	0	41	491	65	130	38	249	38
Lake Brou	5	1	2	164	95	1	208	69	5	2	118	127	11
Lake Brunderee	15	11	8	23	42	0	19	85	15	11	19	17	36
Lake Illawarra	178	175	24	4930	947	2677	3764	300	253	2176	2936	759	46
Lake Macquarie	335	788	15	6513	1498	3459	5778	1378	621	2749	3728	1674	137
Lake Mummuga	3	4	6	76	13	9	40	65	4	15	24	53	5
Lake Tarourga	3	3	0	26	15	0	30	19	2	2	18	15	6
Little Lake (Narooma)	0	6	0	14	0	7	14	0	4	5	10	0	0
Little Lake (Wallaga)	1	1	0	27	3	0	30	6	1	1	24	5	1
Macleay River	2452	20975	354	20037	13302	2194	37852	19092	3032	21856	14919	13947	3361
Maloneys Creek	2	27	1	63	1	31	10	55	28	4	9	51	1
Manning River	2425	5299	274	41387	11829	4386	47246	11066	2578	9270	31580	16476	845
Merimbula Lake	43	39	31	227	90	114	306	0	82	69	158	73	0
Meringo Creek	2	6	0	17	0	0	14	14	2	6	10	7	0
Meroo Lake	0	0	0	203	52	55	80	133	0	51	51	128	21
Estuary	**BCI**					**BCC 2017**			**BCP 2017**				

	Low	Mod. low	Mod.	Mod. high	High	Low	Mod.	High	Low	Mod. low	Mod.	Mod. high	High
Merrica River	0	0	1	64	2	0	4	70	0	1	2	62	1
Middle Camp Creek	2	4	0	20	1	7	7	25	3	6	2	15	0
Middle Lagoon	4	2	4	277	70	17	248	104	4	18	187	126	19
Millards Creek	0	0	0	7	0	6	0	3	0	5	0	2	0
Minnamurra River	39	139	6	1609	446	378	1550	296	98	375	1161	478	109
Mollymook Creek	0	6	0	15	0	7	0	15	4	5	0	12	0
Mooball Creek	621	460	61	1839	171	2277	856	693	826	1430	600	270	25
Moona Moona Creek	34	73	10	241	102	42	20	411	59	63	16	224	97
Moonee Beach Creek	2	101	0	13	0	4	0	118	4	98	0	13	0
Moonee Creek	118	91	23	713	49	419	459	535	125	409	164	273	20
Moruya River	63	158	30	1536	958	509	1853	476	150	449	1065	921	131
Munna Munnora Creek	1	2	0	21	0	9	13	2	2	9	13	0	0
Murrah River	4	6	10	818	192	15	686	79	4	29	442	238	10
Myall River	3047	11318	299	14074	2004	2874	12560	19472	5100	9820	7517	7461	584
Nadgee Lake	34	91	8	5	31	0	11	136	24	22	9	9	19
Nadgee River	3	47	1	159	83	0	16	284	2	47	7	160	74
Nambucca River	511	1598	66	13005	3049	1064	13146	4241	665	2295	10088	4644	535
Nangudga Lake	10	11	6	128	19	15	162	6	15	18	118	19	2
Nargal Lake	1	1	1	2	0	0	2	3	0	0	2	1	0
Narrawallee Inlet	2	175	1	912	229	78	816	458	12	230	589	454	29
Nelson Lagoon	4	4	10	82	91	12	90	97	4	16	30	121	16
Nerrindillah Creek	0	0	0	54	2	3	13	45	0	2	11	42	0
Nullica River	57	81	20	62	18	1	208	3	58	100	33	17	0
Oyster Creek	48	46	9	206	8	26	91	201	49	64	82	118	3
Pambula River	0	5	0	724	334	52	592	130	0	57	291	324	32
Pine Brush Creek	1	1	0	76	1	44	11	23	1	44	11	22	0
Pipe Clay Creek	25	50	2	10	0	18	6	62	32	52	2	1	0
Port Stephens	696	5887	47	4157	961	1995	2335	8110	2250	4538	1225	2967	596
Racecourse Creek (Old Bar)	20	35	1	13	0	29	49	18	37	25	1	5	0
Estuary	**BCI**					**BCC 2017**			**BCP 2017**				

	Low	Mod. low	Mod.	Mod. high	High	Low	Mod.	High	Low	Mod. low	Mod.	Mod. high	High
Racecourse Creek (Ulladulla)	0	7	0	0	0	1	0	6	1	5	0	0	0
Richmond River	2816	9495	263	102806	29860	36502	71398	43471	6142	36219	55635	42510	4711
Ryans Cut	60	98	15	166	58	0	61	344	59	100	23	170	44
Saltwater Creek (Eden)	1	1	1	19	1	0	3	20	1	1	3	16	1
Saltwater Creek (Frederickton)	131	315	12	199	12	304	86	314	258	317	35	53	6
Saltwater Creek (Rosedale)	1	6	0	25	1	19	16	1	7	11	14	1	0
Salty Lagoon	124	94	24	76	13	1	12	344	125	93	29	72	12
Sandon River	196	760	28	2026	143	37	98	4612	197	791	73	1970	116
Shadrachs Creek	0	0	0	26	3	6	14	14	1	5	10	14	0
Shoalhaven River	25	249	15	9635	7806	1651	13290	3019	157	1603	7077	7406	1388
Smiths Lake	42	666	5	419	27	36	107	997	50	668	69	339	6
South West Rocks Creek	55	216	3	27	20	42	24	255	73	209	7	17	16
Spring Creek	3	5	1	25	6	14	23	0	6	10	16	5	0
St Georges Basin	114	933	25	1625	450	362	850	2029	152	1136	574	1017	228
Station Creek	35	346	5	212	24	0	23	618	35	347	11	210	20
Stony Creek	0	217	0	2	0	0	0	221	0	218	0	2	0
Swan Lake	5	72	1	403	17	11	74	430	6	78	65	327	15
Table Creek	0	0	0	49	3	0	3	54	0	0	1	48	2
Tabourie Lake	9	53	3	746	35	89	182	612	19	113	152	543	10
Tallow Creek	55	150	7	123	5	205	46	88	152	131	22	32	1
Telegraph Creek	3	196	10	1	0	0	1	213	3	195	11	0	0
Termeil Lake	10	7	3	128	22	30	49	127	10	36	36	74	11
Tilba Tilba Lake	3	6	1	208	59	0	264	29	3	6	197	59	9
Tilligerry Creek	1833	7643	202	1975	800	1999	3082	7347	3059	6809	1303	1084	132
Tomaga River	5	4	2	547	195	230	315	235	9	214	199	251	73
Towamba River	2	2	2	710	260	17	502	31	3	21	233	271	1
Tuggerah Lake	423	1636	58	8613	1762	5608	6860	1833	1201	4650	4890	1382	253
Tuross River	1	2	14	4182	1390	130	3758	533	1	126	2443	1502	158
Estuary	**BCI**					**BCC 2017**			**BCP 2017**				

	Low	Mod. low	Mod.	Mod. high	High	Low	Mod.	High	Low	Mod. low	Mod.	Mod. high	High
Tweed River	618	1728	108	7036	8059	11467	5414	889	1657	10769	3213	1733	182
Twofold Bay	36	58	18	9	2	15	93	19	41	62	16	2	0
Ulladulla	0	1	0	0	0	3	0	0	1	0	0	0	0
Wagonga Inlet	3	1	2	256	67	46	247	70	3	48	150	113	5
Wallaga Lake	14	7	3	1557	238	44	1023	186	14	50	737	306	33
Wallagoot Lake	1	0	10	239	140	8	278	111	0	10	189	134	50
Wallis Lake	3131	7702	331	24557	3594	2915	20428	16744	4175	7909	15913	9674	1313
Wapengo Lagoon	2	14	1	469	211	7	614	122	2	20	381	263	25
Washerwomans Creek	0	12	0	6	0	0	0	19	1	11	0	6	0
Werri Lagoon	3	14	1	301	93	50	325	30	14	39	261	79	11
Willinga Lake	0	2	0	169	37	15	55	147	0	17	40	123	26
Wollumboola Lake	3	4	15	205	77	16	52	248	4	26	32	171	63
Wonboyn River	163	124	263	2256	98	2	215	1278	163	130	413	690	56
Woodburn Creek	2	2	2	167	11	0	8	186	2	3	4	166	7
Woolgoolga Lake	6	8	1	248	9	99	130	63	7	84	115	65	1
Wooli Wooli River	156	801	19	3798	657	61	431	5649	166	839	161	3810	455
Wowly Gully	5	2	9	34	47	1	7	152	5	5	4	33	47

Supplementary Table 4: Area (ha) of low, moderate, high, and total cell scores for blue carbon storage, preservation, generation and permanency in tributaries based on the watershed area. Tributaries are listed in alphabetical order.

Tributary	**Catchment**	**Watershed Area (ha)**	**Storage**				**Preservation**				**Generation**				**Permanency**			
			Low	**Mod.**	**High**	**Total**	**Low**	**Mod.**	**High**	**Total**	**Low**	**Mod.**	**High**	**Total**	**Low**	**Mod.**	**High**	**Total**
Alipou Creek	Clarence River	3361	0	536	172	708	0	719	0	719	0	214	25	239	0	0	719	719
Anchorage Creek	Moruya River	96	0	32	7	38	0	34	4	38	1	6	20	27	0	4	34	38
Belmore River	Macleay River	11446	608	2473	857	3938	608	5019	1493	7120	159	1249	1083	2492	302	1111	5698	7111
Bilambil Creek	Tweed River	31	0	0	0	1	0	1	0	1	0	1	0	1	0	0	1	1
Boambee Creek	Boambee Creek	569	0	100	1	101	0	101	0	101	0	1	0	1	0	0	101	101
Boggy Creek	Bellinger River	71	0	26	40	67	0	54	14	68	4	46	7	57	0	13	54	68
Broadwater Creek	Clarence River	4109	0	565	221	786	0	535	368	903	61	151	86	299	0	316	587	903
Camp Creek	Clarence River	464	0	119	120	239	0	283	0	283	0	174	49	223	0	0	283	283
Chickiba Creek	Richmond River	222	12	47	31	90	12	4	99	115	15	2	13	30	1	82	33	115
Christies Creek	Cudgera Creek	2112	356	310	68	734	356	376	4	736	75	76	40	190	271	0	464	736
Clybucca Creek	Macleay River	27635	0	3563	863	4426	0	8417	157	8574	17	1472	1068	2557	0	154	8402	8556
Cobaki Creek	Tweed River	1022	0	45	4	49	0	49	0	49	0	4	0	4	0	0	49	49
Coldstream River	Clarence River	1492	0	416	190	606	0	707	0	707				0	0	0	707	707
Condong Creek	Tweed River	741	0	102	139	241	0	241	0	241	0	151	3	153	0	0	241	241
Coolongolook River	Wallis Lake	10677	0	1194	14	1208	0	1207	0	1207	0	18	1	19	0	0	1208	1208
Crawford River	Myall Lakes	12195	0	2177	67	2244	0	2131	114	2244	0	80	3	83	0	9	2237	2245
Croobyar Creek	Narrawallee Inlet	3422	0	229	69	298	0	292	9	301	1	66	8	75	0	7	292	298
Crookhaven Creek	Crookhaven River	8681	0	2184	1482	3666	0	3515	166	3681	50	1421	1009	2479	0	159	3507	3666

Tributary	**Catchment**	**Watershed Area (ha)**	**Storage**				**Preservation**				**Generation**				**Permanency**			
			Low	**Mod.**	**High**	**Total**	**Low**	**Mod.**	**High**	**Total**	**Low**	**Mod.**	**High**	**Total**	**Low**	**Mod.**	**High**	**Total**
Crookhaven River	Crookhaven River	1592	0	590	264	854	0	431	429	860	100	154	283	537	0	372	482	854
Cubba Cubba Creek	Manning River	88	0	36	49	85	0	88	0	88	0	72	12	84	0	0	88	88
Cullendulla Creek	Cullendulla Creek	54	0	9	3	12	0	9	3	12	0	2	2	4	0	3	9	12
Dignams Creek	Wallaga Lake	9454	0	228	13	241	0	243	0	243	0	13	3	15	0	0	241	241
Dinsey Creek	Tweed River	61	0	19	38	57	0	59	0	59	0	51	5	56	0	0	59	59
Duck Creek (East Canal)	Richmond River	190	0	74	70	143	0	170	1	171	0	102	31	132	0	0	170	170
Duck Creek	Lake Illawarra	1450	0	264	1	265	0	258	0	258	0	1	0	1	0	0	265	265
Duck Creek	Richmond River	1159	0	39	9	48	0	49	0	49	0	11	1	12	0	0	49	49
Dulguigan Creek	Tweed River	263	0	120	98	219	0	224	0	224	0	182	34	216	0	0	224	224
Dunbible Creek	Tweed River	3834	0	381	8	390	0	390	0	390	0	9	0	9	0	0	390	390
Dungarubba Creek	Richmond River	411	0	176	167	343	0	228	174	402	38	130	68	237	0	162	241	402
Dungay Creek	Tweed River	1003	0	140	1	141	0	141	0	141	0	1	0	1	0	0	141	141
Duroby Creek	Tweed River	1218	0	54	20	74	0	74	0	74	0	23	2	25	0	0	74	74
Emigrant Creek Canal	Richmond River	36	0	16	13	30	0	28	4	32	1	20	5	25	0	3	28	31
Empire Vale Creek	Richmond River	282	6	119	105	230	6	272	0	278	0	154	46	201	5	0	273	278
Fernbank Creek	Hastings River	749	0	161	90	251	0	310	0	310	0	156	59	214	0	0	309	309
Hursley Creek	Hastings River	491	0	363	14	377	0	386	6	392	1	16	5	22	0	6	386	392
Jellat Jellat Gully	Bega River	2127	0	248	54	302	0	303	0	303	0	54	178	232	0	0	302	302
Jerrara Creek	Minnamurra River	103	0	11	12	23	0	23	0	23	0	15	0	15	0	0	23	23
Tributary	**Catchment**		**Storage**				**Preservation**				**Generation**				**Permanency**			

		Watershed Area (ha)	Low	Mod.	High	Total	Low	Mod.	High	Total	Low	Mod.	High	Total	Low	Mod.	High	Total
Kinchela Creek	Macleay River	3166	467	779	255	1501	469	2203	413	3085	63	391	426	880	78	366	2640	3084
Kings Creek (south)	Brunswick River	28	0	3	3	6	0	5	6	10	1	3	1	4	0	5	5	10
Kooloonbung Creek	Hastings River	327	0	14	4	18	0	15	4	19	0	3	0	3	0	1	17	18
Lansdowne River	Manning River	10085	0	3881	3	3884	0	3883	0	3883	0	5	0	5	0	0	3884	3884
Leddays Creek/McLeods Creek	Tweed River	2319	0	793	641	1434	0	965	590	1554	202	708	259	1170	0	585	969	1554
Leos Creek	Twofold Bay	1695	4	21	3	28	4	22	2	28	1	3	2	6	4	0	24	28
Little Branch Creek	Port Stephens	4031	0	1352	3	1355	0	1355	0	1355	0	4	0	5	0	0	1355	1355
Little Bumbo Creek	Tuross River	1733	0	28	1	28	0	29	0	29	0	1	0	1	0	0	28	28
Macquarie Rivulet	Lake Illawarra	10339	0	1940	93	2033	0	2001	0	2001	0	115	3	117	0	0	2033	2033
Maguires Creek	Richmond River	3681	0	44	0	44	0	44	0	44				0	0	0	44	44
Malabar Creek	Moruya River	2469	0	320	104	424	0	350	87	437	14	82	140	236	0	75	348	424
Marshalls Creek	Brunswick River	3096	0	689	80	769	0	770	0	770	0	92	5	96	0	0	770	770
Mollymook Creek	Mollymook Creek	265	6	15	0	21	6	11	4	21	0	0	0	0	1	0	20	21
Mondrook Creek	Manning River	13	0	11	2	13	0	12	0	12	0	3	0	3	0	0	13	13
Mosquito Creek Canal	Richmond River	230	108	51	63	222	108	121	0	229	13	92	24	130	71	0	158	229
Mullet Creek	Lake Illawarra	7040	0	1907	179	2086	0	2123	0	2123	0	219	33	253	0	0	2106	2106
Mullumbimby Creek	Brunswick River	2205	0	589	35	624	0	624	0	624	0	36	0	37	0	0	624	624
Nangudga Creek	Nangudga Creek	653	0	104	8	112	0	113	1	114	0	8	1	10	0	0	112	112
Ocean Shores (south)	Brunswick River	11	0	1	1	2	0	0	2	2	0	0	0	0	0	1	1	2
Tributary	**Catchment**		**Storage**				**Preservation**				**Generation**				**Permanency**			

		Watershed Area (ha)	Low	Mod.	High	Total	Low	Mod.	High	Total	Low	Mod.	High	Total	Low	Mod.	High	Total
Oyster Creek	Manning River	167	9	1	3	13	9	0	4	13	2	0	1	4	8	4	1	13
Pelican Bay	Manning River	26	0	16	4	21	0	16	9	25	3	8	8	20	0	9	17	26
Pipeclay Canal	Manning River	4179	0	1976	47	2023	0	2010	7	2017	3	56	10	69	0	7	2017	2024
Poverty Creek	Clarence River	935	0	242	198	440	0	497	0	497	0	311	78	389	0	0	497	497
Reserve Creek	Cudgen Creek	4163	0	580	266	846	0	767	84	851	18	241	11	270	0	75	777	851
Saltpan Creek	Crookhaven River	349	0	229	115	344	0	0	344	344	106	0	120	226	0	340	4	344
Saltwater Creek	Richmond River	366	68	49	23	140	68	80	0	148	2	39	14	54	18	0	130	148
Saltwater Creek (West)	Port Stephens	197	14	0	0	14	15	0	0	15	0	0	12	12	0	0	14	14
Saltwater Inlet	Macleay River	46	29	11	4	44	29	10	7	46	1	6	4	11	11	1	34	46
Southgate/Alumy Creek	Clarence River	4698	0	888	961	1849	0	1951	0	1951	0	1240	160	1400	0	0	1951	1951
Sportsman Creek	Clarence River	30284	0	691	398	1089	0	1289	0	1289	0	582	159	740	0	0	1289	1289
Spring Creek	Spring Creek	480	0	15	2	17	0	16	0	16	0	2	0	2	0	0	17	17
Stoney Creek	Lake Brou	1543	0	18	0	18	0	18	0	18				0	0	0	18	18
Swan Creek	Clarence River	198	0	64	87	151	0	160	0	160	0	108	13	121	0	0	160	160
Tandingulla Creek	Shoalhaven River	1823	0	745	150	894	0	897	0	897	0	150	203	352	0	0	894	894
The Branch River	Port Stephens	12804	0	3044	1	3045	0	3045	0	3045	0	2	0	2	0	0	3045	3045
Tuckean Broadwater	Richmond River	21707	0	3899	2738	6636	0	5750	1990	7740	349	2488	776	3613	0	1677	6060	7736
Tweed River	Tweed River	57074	0	1707	62	1769	0	1770	0	1770	0	67	2	69	0	0	1770	1770
Victoria Creek	Tilba Tilba Lake	1084	0	129	9	138	0	139	0	139	0	9	1	10	0	0	138	138
Tributary	**Catchment**		**Storage**				**Preservation**				**Generation**				**Permanency**			

		Watershed Area (ha)	Low	Mod.	High	Total	Low	Mod.	High	Total	Low	Mod.	High	Total	Low	Mod.	High	Total
Wallamba River	Wallis Lake	27281	0	7100	40	7139	0	7136	0	7136	0	51	2	52	0	0	7141	7141
Watt Creek	Nambucca River	266	0	55	70	125	0	137	0	137	0	85	7	92	0	0	137	137
Williams River	Hunter River	117555	0	926	433	1358	0	1376	0	1376	0	639	113	752	0	0	1403	1403

Supplementary Table 5: Area (ha) of low, moderate and high cell scores for BCI, BCC (2007 and 2017) and BCP (2007 and 2017) in tributaries based on the watershed area. Tributaries are listed in alphabetical order.

Tributary	BCI					BCC 2017			BCP 2017				
	Low	Mod low	Mod	Mod high	High	Low	Mod	High	Low	Mod low	Mod	Mod high	High
Alipou Creek	0	11	0	469	239	151	474	94	0	161	284	238	35
Anchorage Creek	0	0	0	12	27	2	30	8	0	1	10	21	6
Belmore River	305	3528	42	1135	2195	151	2788	4870	363	3567	222	1812	1240
Bilambil Creek	0	0	0	0	1	0	1	0	0	0	0	1	0
Boambee Creek	0	0	0	100	1	73	26	2	0	73	26	3	0
Boggy Creek	0	1	0	14	53	6	62	0	0	7	13	48	0
Broadwater Creek	0	117	0	549	237	5	371	527	0	122	252	393	136
Camp Creek	0	44	0	16	223	239	22	21	35	213	0	25	9
Chickiba Creek	1	37	0	63	15	7	57	62	3	40	24	44	5
Christies Creek	159	162	37	300	78	451	166	119	267	325	128	17	0
Clybucca Creek	125	4130	0	2010	2415	282	5552	3744	234	4161	801	2619	866
Cobaki Creek	0	0	0	45	4	20	28	0	0	20	27	2	0
Coldstream River	0	100	0	122	484	9	259	439	0	110	107	147	343
Condong Creek	0	0	0	87	153	164	76	2	0	164	59	19	0
Coolongolook River	0	0	0	1192	16	44	963	200	0	44	948	216	0
Crawford River	1	2	0	2178	64	118	1025	1120	1	120	970	1146	8
Croobyar Creek	0	0	0	224	74	25	253	28	0	25	190	69	13
Crookhaven Creek	0	0	0	1237	2429	315	2476	896	0	306	813	1951	587
Crookhaven River	0	0	0	417	437	17	403	442	0	16	168	468	199
Cubba Cubba Creek	0	6	0	3	78	4	84	0	0	10	3	75	0
Cullendulla Creek	0	0	0	8	4	1	8	3	0	1	4	6	0
Dignams Creek	0	0	0	225	15	6	210	37	0	6	188	44	3
Dinsey Creek	0	2	0	1	56	56	3	0	2	54	0	2	0
Duck Creek (East Canal)	0	27	0	12	132	141	27	3	25	118	5	22	1
Duck Creek	0	0	0	264	1	27	236	2	0	27	235	3	0
Duck Creek	0	1	0	36	12	1	48	0	0	2	35	12	0
Dulguigan Creek	0	5	0	2	216	217	7	0	5	211	1	7	0
Dunbible Creek	0	0	0	380	9	181	203	5	0	182	196	12	0

Tributary	BCI					BCC 2017			BCP 2017				
	Low	Mod low	Mod	Mod high	High	Low	Mod	High	Low	Mod low	Mod	Mod high	High
Dungarubba Creek	0	59	0	145	198	333	58	11	55	282	37	27	1
Dungay Creek	0	0	0	140	1	69	71	1	0	69	71	1	0
Duroby Creek	0	1	0	49	25	31	43	0	0	31	25	18	0
Emigrant Creek Canal	0	2	0	6	24	22	8	2	2	21	4	4	1
Empire Vale Creek	4	49	0	24	200	243	23	11	47	206	1	23	1
Fernbank Creek	4	57	0	41	211	52	218	51	7	102	8	169	26
Hursley Creek	0	16	0	356	21	73	273	47	0	88	240	64	0
Jellat Jellat Gully	0	0	0	69	232	1	302	3	0	1	66	234	0
Jerrara Creek	0	0	0	11	12	1	22	0	0	1	9	12	0
Kinchela Creek	61	1983	8	226	808	32	1382	1717	67	2004	110	597	308
Kings Creek (south)	0	4	0	3	3	0	10	0	0	4	3	3	0
Kooloonbung Creek	0	0	0	16	3	11	4	3	0	11	4	3	0
Lansdowne River	0	0	0	3881	3	353	3267	264	0	353	3264	267	0
Leddays Creek/McLeods Creek	0	120	0	467	967	1509	46	0	118	1392	27	17	0
Leos Creek	2	1	1	20	3	0	11	0	2	3	3	3	0
Little Branch Creek	0	0	0	1352	3	3	1223	128	0	3	1220	131	0
Little Bumbo Creek	0	0	0	27	1	0	24	6	0	0	22	7	0
Macquarie Rivulet	0	0	0	1938	95	488	1465	144	0	458	1341	227	5
Maguires Creek	0	0	0	44	0	12	32	0	0	12	32	0	0
Malabar Creek	1	0	0	203	221	41	301	95	1	41	125	211	44
Marshalls Creek	0	1	0	673	96	256	525	9	1	240	461	68	0
Mollymook Creek	1	6	0	15	0	7	0	16	4	5	0	12	0
Mondrook Creek	0	0	0	10	2	3	9	0	0	3	8	1	0
Mosquito Creek Canal	48	58	10	8	106	104	48	78	63	125	10	30	1
Mullet Creek	7	20	0	1840	246	933	1336	0	10	820	1127	147	0
Mullumbimby Creek	0	0	0	588	37	82	536	6	0	82	505	37	0
Nangudga Creek	0	0	0	103	10	8	109	1	0	7	95	10	0
Ocean Shores (south)	0	0	0	2	0	2	1	0	0	1	0	0	0
Oyster Creek	6	2	1	4	0	2	7	4	7	2	3	2	0
Pelican Bay	0	8	0	4	14	0	18	7	0	7	2	13	3

Tributary	BCI					BCC 2017			BCP 2017				
	Low	**Mod low**	**Mod**	**Mod high**	**High**	**Low**	**Mod**	**High**	**Low**	**Mod low**	**Mod**	**Mod high**	**High**
Pipeclay Canal	7	1	0	1972	51	73	1500	609	7	63	1303	658	0
Poverty Creek	0	57	0	51	389	248	36	213	20	265	17	38	157
Reserve Creek	0	6	0	594	252	448	398	6	4	445	338	64	0
Saltpan Creek	0	0	0	224	120	11	258	75	0	11	170	134	29
Saltwater Creek	14	61	1	20	51	92	31	25	50	74	11	12	0
Saltwater Creek (West)	12	14	0	0	0	4	0	66	15	11	0	0	0
Saltwater Inlet	8	22	2	7	8	0	7	39	8	22	2	13	2
Southgate/Alumy Creek	0	101	0	449	1400	120	1590	241	1	219	372	1189	169
Sportsman Creek	0	201	0	348	740	2	442	846	0	202	230	301	556
Spring Creek	0	0	0	15	2	6	11	0	0	6	10	1	0
Stoney Creek	0	0	0	18	0	0	14	5	0	0	13	5	0
Swan Creek	0	10	0	30	121	1	158	2	0	10	29	119	2
Tandingulla Creek	0	0	0	542	352	55	783	62	0	54	474	323	41
The Branch River	0	0	0	3044	1	10	1961	1074	0	10	1960	1075	0
Tuckean Broadwater	11	1100	0	3384	3253	1870	3757	2528	163	2586	1824	1976	1199
Tweed River	0	0	0	1700	69	541	1347	23	0	541	1151	76	2
Victoria Creek	0	0	0	128	10	0	147	0	0	0	128	10	0
Wallamba River	0	3	0	7093	45	442	6364	331	0	444	6319	373	0
Watt Creek	0	12	0	33	92	16	73	48	0	28	11	74	24
Williams River	0	75	0	670	658	84	1105	188	4	148	490	683	51