Quantifying trajectories of river recovery through analysis of riparian vegetation regreening and assemblages of geomorphic units

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Key points

- Riparian vegetation cover in catchments of Eastern NSW has increased by 40% on average since the 1950s, with some catchments now reaching 60–80%.
- Geomorphic recovery is not always a linear process and increasing complexity does not always mean recovery is underway.
- The presence of benches and islands, increases in abundance and area of benches, pools and decreases in abundance and area of floodplain steps can signal recovery.
- Bank-attached bars tend to become more compound in structure as recovery progresses.

Abstract

Extensive removal of riparian vegetation and instream wood during the 19th and 20th centuries drove widespread geomorphic changes in southeastern Australian rivers. With improvements in river management practice, signs of geomorphic and vegetative recovery have been detected since the 1980s. Using supervised classification of satellite imagery, we analysed decadal trends in riparian vegetation cover across 20 coastal catchments of NSW, revealing an average 40% increase in riparian vegetation cover since the 1950s, with some catchments now reaching 60–80%.

Vegetation recovery has occurred along with geomorphic recovery, defined as improvements in the geomorphic condition of river structure and function. We used representative river sections to examine geomorphic unit (GU) assemblages across 78 river sections representing eight River Styles. Results show that recovery is not always linear and the pattern and trajectory of recovery varies among River Styles. The presence of benches and islands indicate ongoing geomorphic recovery for most river types, while increases in the abundance and area of pools and benches and decreases in abundance and area of floodplain steps can also signal recovery. Bank-attached bars also become more compound as rivers recover. Increasing complexity does not always mean recovery is underway. The pattern or geomorphic recovery is dependent on the River Style.

Determining indicator GUs and changes in assemblages to ‘look out for’ in the field or on remote sensing images can aid river practitioners in their detection and analysis of recovery, providing invaluable insight for nature-based and recovery-enhancement approaches to river management.

Keywords

River recovery trajectory, riparian vegetation, geomorphic unit, nature-based solutions

Introduction

Clearance of riparian vegetation and removal of instream wood have caused major geomorphic and ecological degradation of rivers in eastern New South Wales (NSW) since European colonisation. Combined with channelisation, river regulation, and sediment extraction, these disturbances have driven significant river adjustments and metamorphosis. Most rivers reached their poorest condition in the early to mid-20th century (Fryirs et al., 2018). Following improved river management and reduced land-use pressures, coincident with a period of minimal flooding, coastal rivers in NSW have shown clear signs of geomorphic and riparian vegetation recovery since the 1980s (Cohen et al., 2022; Fryirs et al., 2018; Zhang & Fryirs, 2023). One cause may be the lack of geomorphically effective floods and associated impacts on vegetation growth. Also, from the 1980s, river management in Australia transitioned from a hard engineering approach to an ecosystem- and process-based approach with a focus on repair and recovery (Fryirs et al., 2013). This combination of factors has led to significant recovery of riparian vegetation (Cohen et al., 2022; Fryirs et al., 2018).

In this paper vegetation recovery is defined as an improvement in the cover of *woody riparian vegetation*. Remote sensing images and machine learning are widely used for automated land cover classification across large areas, with methods such as Support Vector Machine achieving 80–90% accuracy (Duro et al., 2012). Texture indices further improve accuracy and enable discrimination between vegetation types, including woody and non-woody cover (Qian et al., 2020). Open-source datasets such as Sentinel-2 provide high-resolution observations for recent periods (since 2015), while Landsat extends land cover analysis back to 1987 at coarser resolution. When combined with historical aerial imagery, analysis of vegetation cover can be extended to the 1950s (Zhang & Fryirs, 2023).

Geomorphic recovery, defined as the trajectory of a river reach toward *improved structure and function* (Fryirs & Brierley, 2016; Fryirs et al., 2018), is rarely a simple reversal of degradation and seldom occurs systematically. Different parts of a river system adjust at varying rates and along diverse, often non-linear trajectories (Zhang & Fryirs, 2024b). In NSW, the recovery potential of all rivers has been analysed using the River Styles Framework (Fryirs et al., 2021). River Styles are distinct types of rivers that are characterised according to their geomorphic character and behaviour (Brierley and Fryirs, 2005). This foundational research and associated databases provide an opportunity to characterise and quantify the geomorphic characteristics of river recovery for a wide range of river types using reaches at different stages of recovery. Geomorphic units (GUs) are the fundamental building blocks of river channels and floodplains, formed and reworked by erosion, transport, and deposition processes (Brierley & Fryirs, 2005; Fryirs & Brierley, 2022; Wheaton et al., 2015). As they comprise all components of valley bottoms, GUs provide a consistent basis for systematic geomorphic analysis across river systems (Zhang & Fryirs, 2024a). Analysis of GU assemblages can reveal river behaviour, condition, and stages of recovery (Fryirs & Brierley, 2022). Tracking temporal adjustments in GUs provides insight into the processes shaping river morphology. Here, we evaluate whether metrics such as richness, abundance, diversity, evenness, and area proportion of GUs can be used to characterise geomorphic recovery across a range of river types. Geomorphic river recovery includes reorganisation of bed material, low-flow channel formation, the disappearance of some GUs such as sand sheets and reappearance of GUs such as pools, riffles, and benches (Fryirs & Brierley, 2022; Fryirs et al., 2018).

In this paper, we aim to 1) understand the long-term trends in riparian and in-channel vegetation cover at the catchment and regional scale, and use these findings to provide forecasts of possible future riparian vegetation change; 2) characterise the geomorphic recovery trends through analysis of the assemblage of GU for various river types, identify indicator GUs by analysing the presence/absence and prevalence of GUs at different recovery stages; 3) provide guidance on how GU analysis can be used to inform recovery-enhancement approaches to river management.

Methods

Riparian vegetation mapping and analysis

Riparian vegetation was analysed across 20 coastal catchments in NSW, grouped into North, Central, and South Coast regions (Figure 1). Analysis was conducted on the riparian corridor, which includes the in-channel zone (bounded by macro-channel banks) and riparian zone, defined as a 50 m buffer extending beyond both banks (see Zhang & Fryirs, 2023). In total, 3,268 km^2 of riparian corridor and 19,485 km of stream length were evaluated.

Riparian vegetation change from 1987 to 2021 was quantified using satellite imagery from Landsat (1987, 1995, 2004, 2013, 2021) and Sentinel-2 (2021), accessed through Google Earth Engine. The full method of analysis is published in Zhang & Fryirs (2023). Surface reflectance products with atmospheric correction were used. Images were selected to prioritise minimal cloud cover during the peak growing season (September); where unavailable, the closest cloud-free dates were chosen. Land cover was classified into four classes—woody vegetation, non-woody vegetation, bare surfaces, and water—using a Support Vector Machine (SVM) supervised classification approach. Predictor variables included red, green, blue, and near-infrared bands, alongside normalised difference vegetation index (NDVI), normalised difference water index (NDWI), and texture metrics (angular second moment). Training and testing datasets were derived from systematically sampled points across the 20 catchments and validated against high-resolution aerial imagery. For Sentinel-2, 863 samples were generated, with a 70/30 split for training and testing. Consistent training datasets with 911 training points and 191 – 196 testing points were applied across Landsat time slices. Model parameters (cost and gamma) were optimised through cross-validation, and classification performance was evaluated using confusion matrices, overall accuracy, producer and user accuracy, and kappa coefficients.

To extend the analysis beyond the 1980s, historical aerial imagery from the 1950s–1960s and 1970s–1980s were used for three representative trunk streams (Nambucca, Hunter, and Bega Rivers) to represent north, central and south coast regions, covering 89 km^2 and 400 km of channel length. Images were georeferenced in ArcGIS and standardised by converting to greyscale and resampling to a 3.15 m spatial resolution. Vegetation was manually digitised and classified into fully covered (≥70% canopy cover) and partly covered (30–70% canopy cover), with classification accuracy evaluated using independent testing points. Land cover classification achieved high accuracy, with 95.6% for Sentinel-2 and 93.3–96.9% for Landsat, while historical imagery achieved 83.3–85.8%.

Geomorphic unit mapping and analysis

A total of 78 river sections (Figure 1) were selected across eight River Styles and three valley settings. For each River Style, 3–4 reaches were selected for each of three recovery stages. Recovery stages were identified using the NSW River Styles database (Fryirs et al., 2021), which is based on river morphology and processes. In general, Low Recovery Potential (LRP) represents river sections with uniform channel morphology, unstable bars and banks. Moderate Recovery Potential (MRP) indicates partial establishment of bars, benches, and islands. High Recovery Potential (HRP) reflects well-developed and stable geomorphic units, including pools and riffles (Fryirs et al., 2018; Fryirs and Brierley 2016; Brierley and Fryirs, 2005).

Geomorphic units (GUs) were mapped using a semi-automated framework based on the Geomorphon method. The full method of analysis is published in Zhang & Fryirs (2024a). LiDAR-derived digital elevation models (DEM) were used to delineate valley bottom, bankfull channel, and active channel zones in ArcGIS. Geomorphon models classified terrain into landform types, which were then grouped and refined using additional criteria, including fluvial zone, relative elevation above the water surface, proximity to channel margins, and water coverage. Water cover layers derived from SVM classification of Sentinel-2 imagery enabled identification of pools and ponds based on water extent during baseflow and drought conditions. The resulting GU mapping was refined through manual correction and verification against aerial images, producing 20 GU types.

For each river section, geomorphic richness, abundance, and diversity (Shannon index, evenness, and dominance) were calculated using both unit counts and area (Zhang & Fryirs, 2024b). Metrics were normalised by channel length and mean channel width to ensure comparability. Statistical differences among recovery stages were assessed using ANOVA and paired t-tests implemented in R.

Results

Recovery of riparian vegetation has been dramatic

Over the past 70 years, woody vegetation cover in riparian corridors across coastal NSW has increased substantially at both catchment and regional scales (Figure 1). In the 1950s–1960s, woody vegetation cover was extremely low (<20%) across three representative trunk streams (e.g., as low as 6% in the Hunter River). By 1987, most catchments had increased to 20–45%, and by 1995 all catchments exceeded 30%. From 1995 onward, a steady regional increase occurred, with most catchments surpassing 40–50% by 2013 and continuing gradual gains to 2021, when many exceeded 50% and a maximum of 77% was recorded (Moruya catchment). Only the Hunter and Tweed catchments remained comparatively lower (44%) in 2021 (Figure 1).

Across all coastal catchments, riparian woody vegetation cover has increased by 40% on average (≈1313 km^2 of 3268 km^2) since the 1950s, with a 18% increase since 1987 alone. Temporal vegetation recovery trajectories differ among catchments. For example, the Nambucca has most of the increase occurred before 2004, and remained steady since, the Bega shows the increase accelerating since 2004, and the Hunter displays a more uneven pattern, with increases occurring before 1995 and after 2013. Overall, riparian and in-channel vegetation changes are strongly coupled.

Geomorphic river recovery varies across different river sections

Changes in GU richness, abundance, and diversity show that geomorphic river recovery vary across River Styles and valley settings. When all 78 river sections are combined, spatial complexity generally increases with recovery, reflected in higher richness, abundance, and areal diversity, alongside a reduction in dominant units (occupying >50% of macrochannel area). At the River Style (reach) scale, recovery patterns are more diverse and often non-linear (Figure 2). Confined rivers show a linear increase in richness, abundance, and diversity, with greater diversity driven mainly by the emergence of new GU types during recovery. Partly confined rivers exhibit variable patterns with fluctuations in richness, abundance and diversity measures as recovery progresses. Laterally unconfined rivers display non-linear increases in abundance, diversity, and evenness, with higher diversity resulting from a more even distribution of existing GUs. Channelised fill rivers contrast with the prevailing trend observed in other laterally unconfined River Styles with a reduction in diversity in advanced recovery stages.

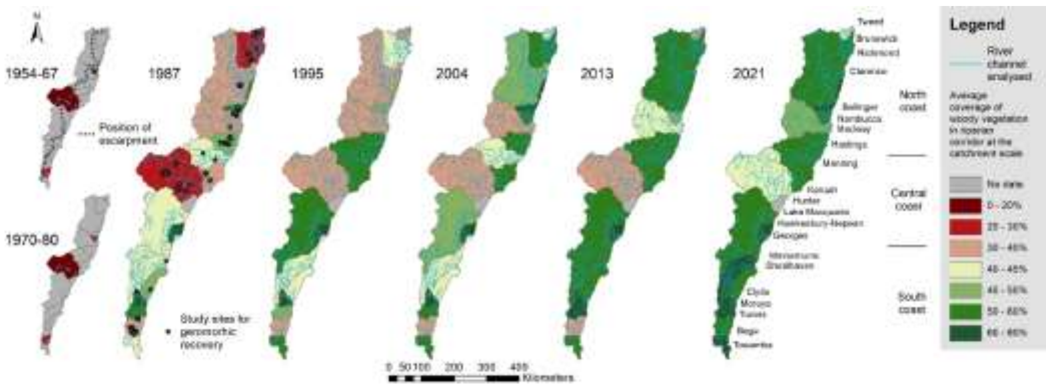

Figure 1 Woody vegetation coverage in riparian corridor from the 1950s to 2021, summarised at the catchment scale. Modified from Zhang & Fryirs (2023)

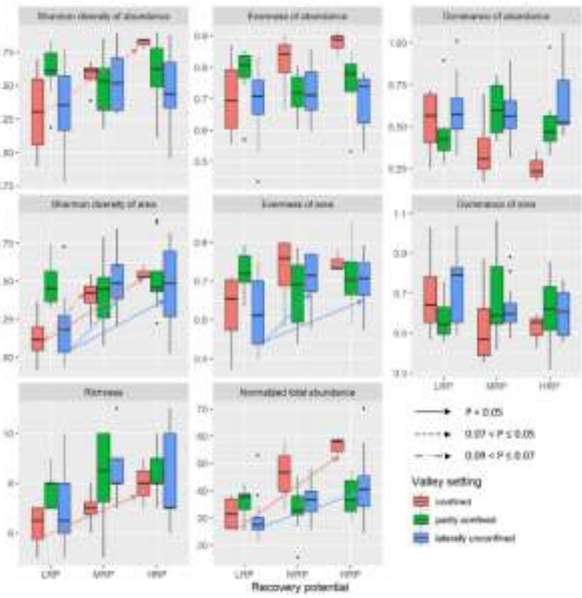

Figure 2 Changes in the richness, abundance, and diversity of GUs as recovery progresses from LRP to MRP and HRP for valley settings within all 78 river sections combined. Colour of the arrows corresponds to the colour of valley settings. Form of the arrows indicates the significance level of the change between the recovery stage at each end of the arrow. Source: Zhang & Fryirs (2024b)

Changes in individual geomorphic unit indicate recovery

Of the 20 mapped GU types, half occur across all recovery stages and River Styles, while the remaining units are specific to particular stages or River Styles. Benches, islands, and ponds are key indicators of recovery across different River Styles. Analysis of abundance and area changes in individual GU types show that benches and pools become progressively more common from LRP to HRP, while floodplain steps diminished as the recovery progresses (Figure 3). Benches show the strongest and most consistent response, with significant increases in abundance, total area, and proportional area, indicating greater prevalence in more advanced recovery stages. Pools display a weaker but generally positive trend, with increasing abundance and higher area in MRP and HRP, suggesting gradual expansion during recovery. In contrast, floodplain steps significantly decrease in abundance and show reduced area, transitioning from widespread unit in LRP to rare unit in HRP. Unit bank-attached bars significantly increase in abundance but show no change in total area, reflecting a reorganisation of large unit bank-attached bars into smaller ones as recovery progresses. Compound bank-attached bars show no significant change in abundance. However, their proportional area shows a weak increase, while unit bank-attached bar area declines. This suggests a gradual shift towards more complex bar forms (i.e. unit toward compound), particularly in partly confined gravel-bed rivers.

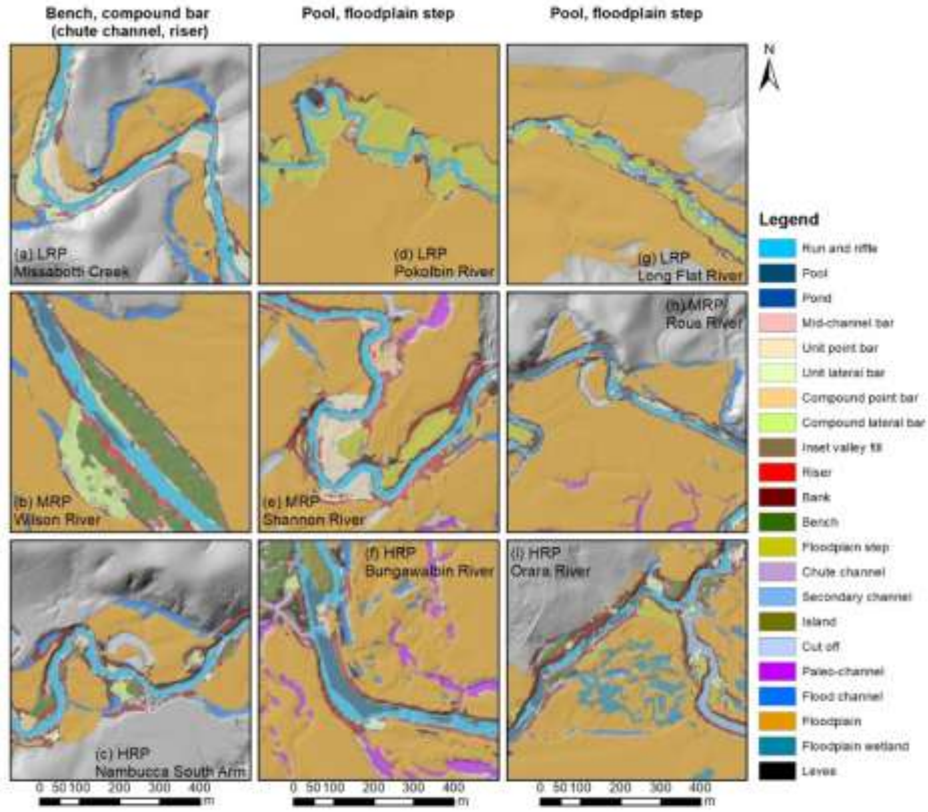

Figure 3 Examples of development (a-c) bench, compound bar (chute channel and riser), (d-f) pool and floodplain step along sand bed rivers (g-i) pool and floodplain step along gravel bed rivers as recovery stage advances. Source: Zhang & Fryirs (2024b)

Discussion

Geomorphic river recovery patterns vary by River Style

Geomorphic river recovery patterns vary by River Style, reflecting differences in behaviour and adjustment capacity (Williams et al., 2020; Zhang & Fryirs, 2024b). Rivers with greater adjustment capacity (e.g., rivers with wider valley bottoms and sand or gravel textures that allow greater geomorphic adjustments of the channel and instream GUs) tend to reorganise assemblages of GU more actively during recovery than those with limited capacity to adjust (Brierley & Fryirs, 2005; Fryirs & Brierley, 2016; Fryirs & Brierley, 2022). This work demonstrates that simple measures such as presence/absence or comparison to reference conditions are insufficient to detect recovery and that river recovery is often non-linear and varies by River Style. Therefore, more nuanced, style-specific analyses are needed. This work also busts early ideas that increasing geomorphic complexity of rivers always equals an improvement in condition and recovery (Wohl, 2016).

Confined rivers show a clear recovery trajectory, with increasing GU richness, abundance, evenness, and diversity (Figure 4-1). The increase is greater between LRP and MRP stage, with GUs such as unit lateral bars disappearing and bedrock outcrops reappearing. Similarly, laterally unconfined rivers (excluding channelised fill types) display overall increases in these metrics (Figure 4-1), particularly from LRP to MRP. These patterns suggest that these rivers have sufficient capacity to adjust and (re)work their GUs and assemblages. Partly confined rivers exhibit more irregular recovery patterns (Figure 4-2), with fluctuations or minimal change across recovery stages. Rather than increasing complexity, these systems tend toward greater stability, including better defined low-flow channel and increasing dominance of units such as runs and riffles in advanced recovery stages. Channelised fill rivers follow a contrasting trajectory (Figure 4-3). GU evenness declines, while richness and diversity peak at MRP and then decrease towards HRP. This indicates a shift from relatively complex early stages to simpler later stages. The findings demonstrate that river recovery does not always increase geomorphic diversity (Fryirs & Brierley, 2009; Fryirs & Brierley, 2016; Wohl, 2016).

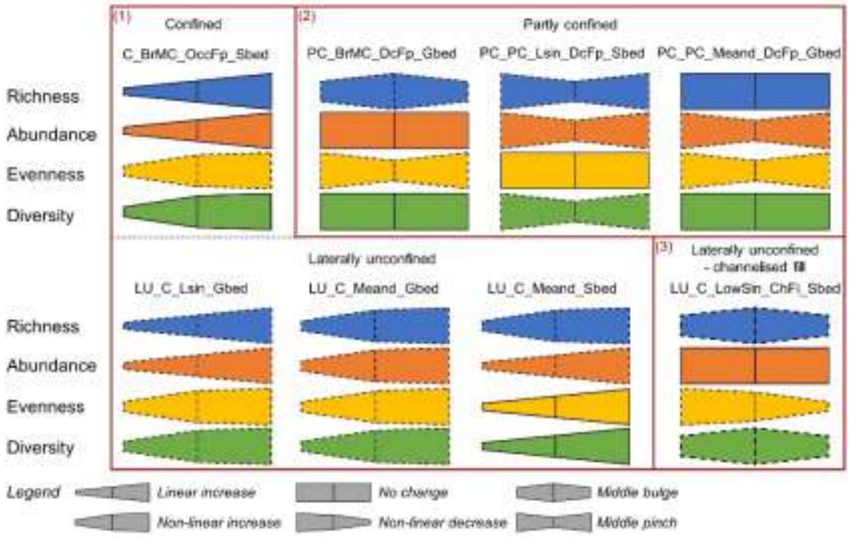

Figure 4 Geomorphic river recovery patterns for eight River Styles. The dashed lines indicate observable but non statistically significant changes. Source: Zhang & Fryirs (2024b)

Signals of geomorphic river recovery and management implications

This study demonstrates the outcomes of river self-adjustment, emphasising the importance of passive or natural processes in river recovery (Fryirs & Brierley, 2016). River recovery has been happening in coastal catchments of NSW since the 1980s, largely via self-healing. Indicator GUs provide a useful foundation for detecting whether recovery is occurring. Effective assessment requires consideration of changes in indicator GU metrics (Table 1) and River Style specific recovery patterns (Figure 4). Understanding these differences helps set realistic goals, timeframes, and expectations for recovery as part of river management practice. Importantly, managers must assess whether recovery can be enhanced within practical timeframes, by considering specific river recovery pathways and the time it takes for river recovery to occur. At larger scales, successful recovery enhancement requires identifying and addressing major limiting factors such as climate change, land use, and policy influences (Fryirs & Brierley, 2016). Understanding how river recovery is occurring and whether management interventions will enhance recovery is critical for effective management (Fryirs et al., 2018).

Table 1 River recovery metrics that can be used to detect changes in indicator units. Source: Zhang & Fryirs (2024b)

Geomorphic unit	Metrics that can be used to detect geomorphic river recovery
Bench	Presence (✓) and increase in abundance (🡅) and area (🡅)
Island	Presence (✓)
Pond	Presence (✓) (for channelised fill rivers)
Pool	Increase in abundance (🡅) and area (🡅)
Bank-attached bar (point & lateral)	Increase in abundance (🡅) but not in total area (🡆) (for sand bed rivers)
Floodplain step	Decrease in abundance (🡇) and area (🡇)

Forecasting future vegetative river recovery

Given the coeval nature of geomorphic and vegetative river recovery in eastern NSW, detecting ongoing recovery and forecasting future progress and patterns are crucial steps if river management is to enhance recovery into the future (Zhang & Fryirs, 2023). To demonstrate how we can use the findings on vegetative recovery for forecasting, the regressions for the region and sub-regions change trend were used to produce possible future change envelopes for riparian woody vegetation coverage for a range of climate, management and natural disaster scenarios that are commonly expected (Figure 5). Forecasts extend from current vegetation levels, and the disturbance impacts are converted into coverage setbacks through expert judgement (Zhang & Fryirs, 2023).

In Figure 5, Scenario A ("do nothing"), woody vegetation cover increases through natural recruitment, reaching 70% cover by 2055 under medium growth. With the application of best and worst scenarios, this timeframe can be shortened or prolonged by 10 years. Scenario B considers a revegetation program (2040–2045) adding 1% cover, may reduce the time to 70% cover to 2052. A moderate disturbance (Scenario C) removing 5% vegetation (2040–2045), may delay recovery to 70% cover by 7–14 years. Two such disturbances within a decade (Scenario D), may cause a 3–6% net decline and a 15–25 year setback. A catastrophic 20% loss (Scenario E), such as severe bushfire, may result in a 30–40 year setback, with current vegetation levels not recovered until 2060. Scenario F considers climate change driven growth enhancement (+0.2% annually), may reduce time to 70% cover by 10 years.

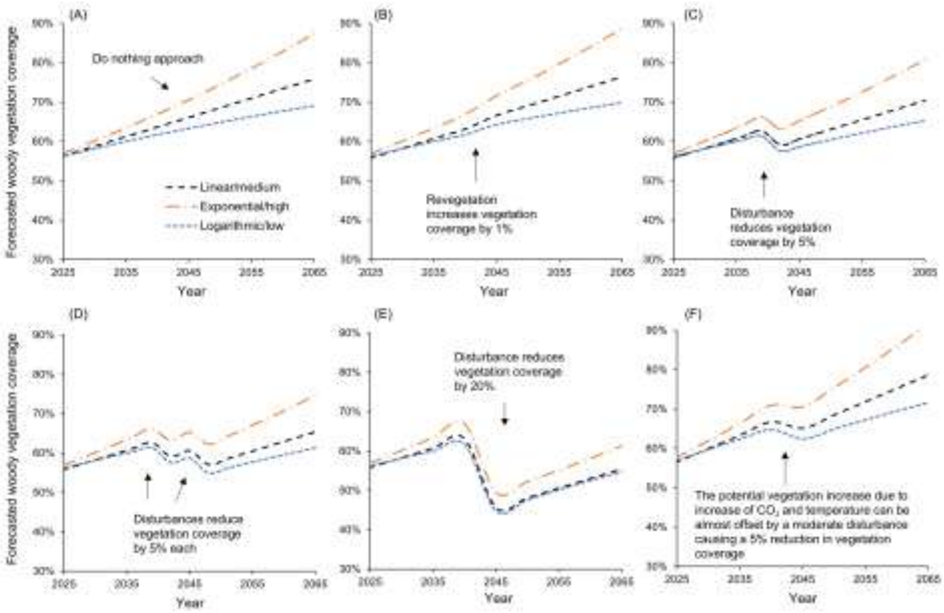

Figure 5 Forecasts of riparian woody vegetation cover for various climate, management and natural disaster scenarios. Source: Zhang & Fryirs (2023)

Conclusions

We mapped geomorphic and vegetative recovery across 20 coastal catchments of NSW. Since the 1950s, substantial increases in riparian woody vegetation have occurred across all catchments, coinciding with measurable reorganisation of GU assemblages. Recovery can be detected using indicator GUs and changes in their assemblages. Benches and islands are key indicators of recovery across most River Styles. This study demonstrates that river recovery is not linear and varies among River Styles, highlighting the importance of understanding the specific recovery patterns for different river types. Spotting these patterns and indicators in the field or on imagery provides a practical tool for identifying and assessing river recovery, supporting nature-based and recovery-enhancement river management. The findings from this paper can be used as a basis for undertaking future forecasting of geomorphic and vegetative river recovery in these catchments.

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