An agricultural innovation systems framework for improving water quality in the Great Barrier Reef catchments

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Abstract. The Australian and Queensland governments have invested over A$1 billion in the last 20 years to arrest ecosystem decline and improve water quality in the Great Barrier Reef (GBR). However, improving water quality is a 'wicked' problem and improvements to date have been insufficient for the scale of change needed. Most existing models used to address GBR water quality do not incorporate Agricultural Innovation Systems (AIS) principles, tending to address it as a 'tame' problem. While these approaches provide valuable insights, they do not address the complexity of the systems interactions. We develop an AIS framework designed to guide research and assist policy makers to recognise the elements of the system that are central to practice change and innovation. It incorporates an AIS model for the key agricultural industries affecting Great Barrier Reef water quality and represents macro, meso and micro level governance and innovation processes affecting the design, use and evaluation of changes in the agricultural innovation systems for those industries. This is the first AIS model designed specifically to address improving water quality in the GBR that can be used for designing, funding and implementing programs and projects from the micro through to the macro levels of the system.

Keywords: wicked problems; Great Barrier Reef; water quality; agricultural innovations systems; governance framework

Background

Over the last 20 years, the Australian and Queensland governments have invested more than $1 billion to reduce the impacts of rural and urban runoff on water quality in the Great Barrier Reef (GBR). From 2017 to 2022, A$390 million was spent (Coggan et al. 2024) to achieve the Reef 2050 Water Quality Improvement Plan targets. This investment aimed to (i) promote adoption of minimum practice standards, (ii) encourage innovation beyond the minimum practice standards, and (iii) remediation of streambanks, gullies, riparian vegetation and wetlands (Australian Government & Queensland Government 2018; Dean et al. 2023).

Many of the targets will not be met (Australian Government & Queensland Government 2024). For example, one 2025 target aims for a 60% reduction in end-of-catchment dissolved inorganic nitrogen loads. The most recently available Reef Report Card (2021–22) indicates progress had reached only 28.4%. If Australia is to protect the GBR, it is crucial to identify ways to accelerate the adoption of management practices that improve water quality.

Improving GBR water quality is a 'wicked' problem

In the 2017 Scientific Consensus Statement (SCS), Eberhard et al. (2017) describe improving water quality outcomes for the GBR as a 'wicked problem'. Wicked problems have distinct features, including that the problems lack an agreed definition and change over time, amid high uncertainty. In addition, solutions are not clearly right or wrong, just 'better' or 'worse', relying on the judgements of multiple stakeholders. Plus outcomes depend on interactions between stakeholders and political forces, encompassing diverse and contested values about societal goals (Rittel & Webber 1973; Batie 2008). 'Wicked' problems require more than just traditional approaches stemming from natural sciences. Much natural science research addresses what are called 'tame' problems. That is, 'what is' and 'what if' research questions. In contrast, addressing water quality requires us to answer the question of 'what ought to be' (Rittel & Webber 1973; Batie 2008). The answers to this question are contested and do not necessarily coincide with disciplinary paradigms about what will result in the best outcomes (Batie 2008). Hence, when developing solutions, we need frameworks that address this complexity.

Need for an AIS approach to address GBR water quality

Policy instruments used to promote practice change and improve Reef water quality include financial instruments, regulations, suasive instruments (extension), and procedural instruments (or governance) (Dean et al. 2023). Much research examining barriers and enablers of practice change in the GBR focus on narrow aspects of the adoption and innovation processes, such as technology adoption by farmers in a specific industry (e.g. Benn et al. 2010; Bohnet 2015; Greiner 2016; Deane et al. 2018; Eberhard et al. 2021; Fielke et al. 2021). Others discuss governance and processes used to promote change (Dale et al. 2016; Eberhard et al. 2017; Vella & Baresi 2017; Bennett et al. 2018; Queensland Government 2021).

While this research provides valuable insights, it rarely applies broader systems approaches, such as Agricultural Innovations Systems (AIS) principles, that are necessary to address the 'wicked' problem of reef water quality. Within the GBR context, agricultural innovations occur in a complex adaptive system, where models that assume linear adoption pathways have reduced performance (Douthwaite & Hoffecker 2017). Hence, we argue tackling water quality needs to consider complex dynamics within an AIS approach.

An AIS is defined as: 'A network of actors or organizations, and individuals, together with supporting institutions and policies in the agricultural and related sectors, that brings existing or new products, processes, and forms of organization into social and economic use' (Tropical Agriculture Platform 2016, p. x). This is similar to the definitions used by Mytelka (2000), The World Bank (2006) and Rajalahti (2012). Innovation developed within an AIS can be defined as 'the process by which individuals or organizations master and implement the design and production of goods and services that are new to them, irrespective of whether they are new to their competitors, their country, or the world' (Mytelka 2000, p. 18). This broad definition of innovation recognises the importance of context: an innovation in one context may not be an innovation in another context unless it is improved to meet the needs of potential adopters in that context. An AIS also involves learning and development processes, such as when organisations and individuals generate, adapt or share new knowledge, products, and ways of organising. This includes formal and informal governance systems, establishing rules, norms, conventions, and implementation of policies that shape other parts of the system (The World Bank 2006; Rajalahti 2012; Anandajayasekeram 2019; de Boon et al. 2022). The AIS approach was developed to assist development agencies and national governments with the design and implementation of projects that aim to promote agricultural innovation in complex systems.

Despite the acknowledged complexity of improving GBR water quality, no framework integrating AIS principles has been developed for the GBR context. Without an integrated framework, policy and investments risk addressing only parts of the problem and may continue to contribute to the acknowledged shortfall in meeting water quality targets. This paper develops the first AIS framework specifically designed to address this gap. It was created initially to assist with framing the evidence base and the key questions for the 2022 Scientific Consensus Statement question relating to the uptake of recommended management practices to improve water quality outcomes for the GBR.

Objective

The purpose of our framework is two-fold. It may guide design and implementation of policies, projects and programs. It may also support integration of research, development and extension at all levels of the GBR system. It could be used, for instance, when evaluating which policy options are more likely to succeed, or alternatively, to design, implement and evaluate a project to conduct water quality monitoring.

Firstly, we outline an AIS model of key actors and institutions involved in GBR agricultural value chains. Next, we present an AIS framework for assessing macro, meso and micro level governance and innovation processes that affect adoption of innovations by the actors and institutions. The models are separated because incorporating both the actors and the processes in a single model would make it unworkably complex. Finally, we discuss insights from the AIS model and governance framework for researching and promoting practices to improve water quality in the GBR.

Framework development

The framework was developed by synthesis of AIS theory, governance frameworks, behaviour change models, and extension theory, with de Boon et al. (2022) providing the primary theoretical anchor. Each of these theoretical traditions addresses a distinct but important dimension of the innovation system. AIS theory provides the overarching systems perspective; governance frameworks address the structures and processes shaping actor behaviour; behaviour change models explain individual and organisational responses to innovation; and extension theory addresses the processes shape diffusion in agricultural contexts. The approach was deductive in drawing on established AIS theory, but inductive in that it was shaped and refined through its application to the SCS evidence synthesis process.

While integrated governance and systems-analysis frameworks have been applied in NRM contexts (e.g. Dale et al. 2016; Vella et al. 2024), these do not incorporate the full innovation systems perspective of AIS — particularly the emphasis on actor capacities, innovation processes, and the dynamic interactions between governance and practice change across value chains.

An Agricultural Innovation Systems model for GBR value chains

The AIS model for GBR value chains incorporates three levels. These are: (i) the macro context and governance systems, (ii) the meso system of GBR focused actors and agencies, and (iii) the micro system of farmers and upstream and downstream actors for the GBR agricultural value chains (Macro context of the AIS for the GBR value chains

The macro context of the AIS model incorporates insights from several sources (Bronfenbrenner 1992; Murray-Prior et al. 2004; de Boon et al. 2022). It incorporates diverse elements including socio-economic and cultural elements, changing natural environment, policy and legislation, politics, mass media and global markets. ***Natural capital*** for the GBR system encompasses agri-environmental assets (e.g. livestock, crops, soil productivity) and ecological assets (e.g. biodiversity, native vegetation, ecosystem health) that support farm productivity. Natural capital shapes the meso and micro levels of the system. ***International agencies*** shape agricultural, conservation, climate and economic settings e.g. the listing of the GBR as a World Heritage Area by UNESCO (Dale et al. 2016). ***Enabling factors*** include national agricultural and environmental policy, investment and regulatory settings. As outlined by Roseboom (2012, p. 449) these include: '(1) innovation policy and corresponding governance structures to strengthen the broader framework for agricultural innovation policies; (2) regulatory frameworks that stimulate innovation directly … or indirectly … or steer innovation towards preferred outcomes …; and (3) accompanying agricultural investments in rural credit, infrastructure, and markets'. The broader ***national socioeconomic and political context*** incorporates the broader range of capitals relating to economic, human, financial, cultural and social capital and the formal and informal institutions, practices, behaviours and attitudes of the surrounding society.

Meso-micro actors of the GBR agricultural systems

The next level of the system involves actors and agencies associated with the value chains for the main agricultural industries in the GBR area. Within the outer boundary are the meso-level actors involved with the main agricultural value chains of sugar, beef and horticulture. These include the main research, extension, education, regulation, funding and NRM agencies that are involved with these industries. While they are shown as separate, there is considerable overlap, with some agencies involved in research, development, education, extension and funding (e.g. Universities, NRMs and the Queensland Department of Primary Industries). While the value chains are quite different (for example, sugar has its own research, extension and farmer organisations), each has similar elements, particularly in the upstream components. Within the inner boundary are the relationships and information flows between the various actors and, to a lesser extent, logistics for the chains.

Figure 9). The meso and micro system actors and institutions are typically the key targets for policy instruments (e.g. financial, extension) that aim to change management practices for improved water quality. They will vary with each value chain, although there will be overlap.

Macro context of the AIS for the GBR value chains

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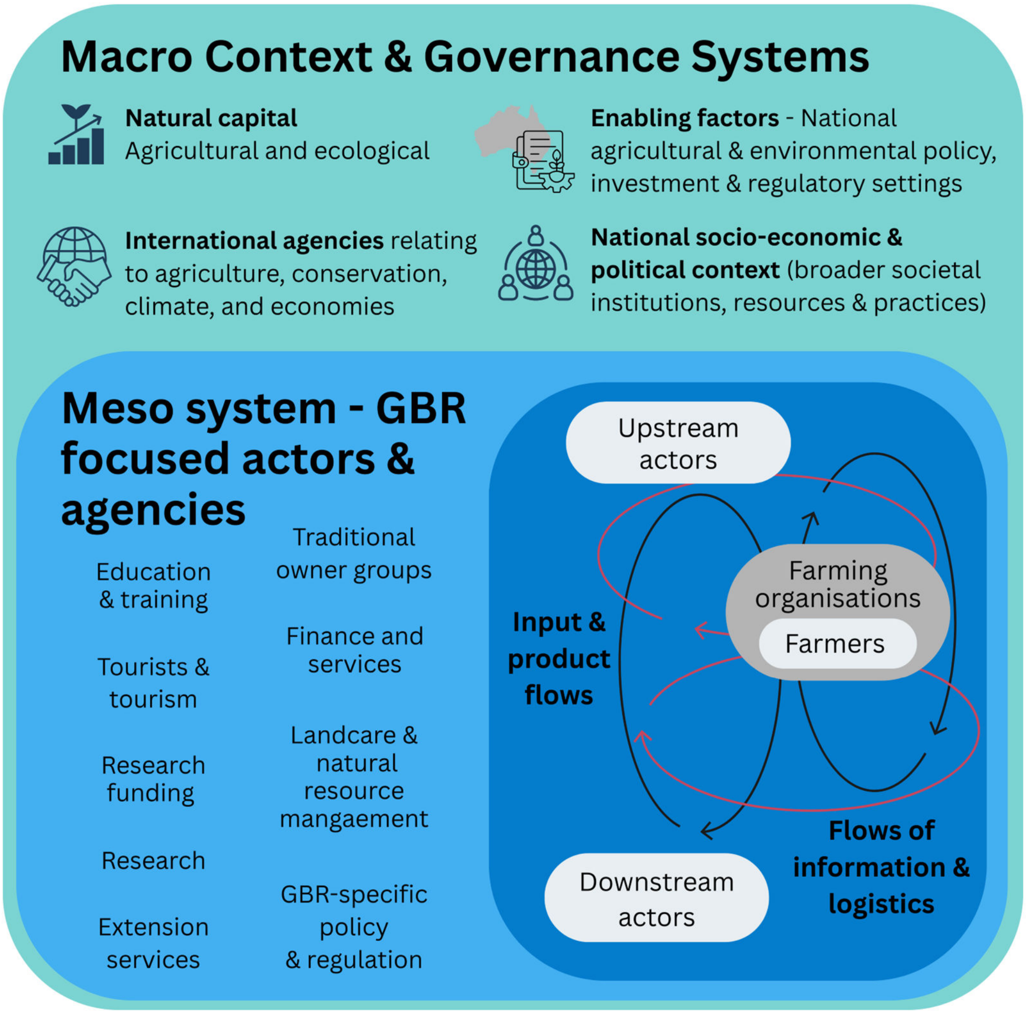
Figure 9: An Agricultural Innovation Systems model of key actors and institutions involved in GBR agricultural value chains



Sources: Murray-Prior et al. (2004); Birner et al. (2009); Rajalahti (2012); Murray-Prior (2020); Paschen et al. (2021); de Boon et al. (2022)

A framework for assessing the key governance and innovation processes

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Figure 9 identifies who is in the system – the actors and structures of the AIS at macro, meso and micro levels, The outer dimension of this framework, the macro context, enabling environment and governance system is consistent with Macro context of the AIS for the GBR value chains

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Figure 9. These macro elements are drivers and constrainers of change. Within the meso-micro system, the innovation processes interact with the capacities and contexts of the value chain actors to create the innovations, particularly those related to management practices which affect agricultural run-off and reef water quality. Perceptions of these practices, and the processes

applied to promote them, hinder or enable their adoption and subsequent impacts on GBR water quality.

Figure 10 provides a detailed analytical framework for diagnosing *how* the processes within the system interact to enable or constrain practice change. It includes the governance system, the context of the key actors, and the innovation processes that are governing, moulding, enhancing and constraining water quality outcomes for the GBR.

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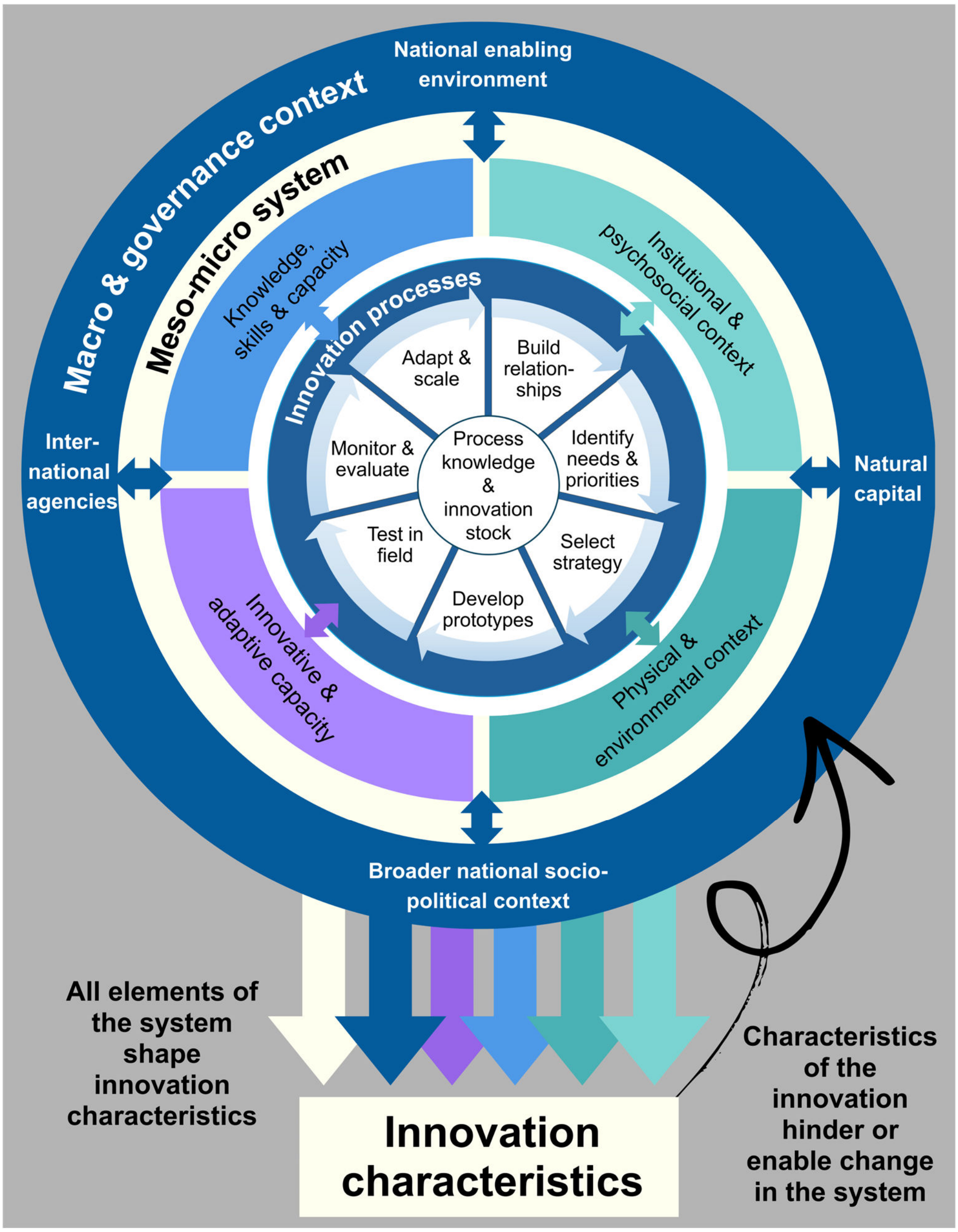
Figure 10: An Agricultural Innovation Systems (AIS) framework for assessing macro, meso and micro level governance and innovation processes affecting adoption of innovations

Sources: Adapted from de Boon et al. (2022), but including concepts from Tully (1966), Bryant (1989);



Michie et al. (2011); The World Bank (2012); Teng & Oliveros (2016); Dessart et al. (2019); Murray-Prior (2020); Williams et al. (2021)

Macro context and governance system

Figure 10 emphasises the structures and processes used by public and private actors in that model to interact, exercise power, make and implement decisions that aim to steer the AIS towards improving reef water quality (de Boon et al. 2022). Vella et al. (2024, p. 12) suggest 'human actions represent, and indeed are mediated by, the wider governance system that guides behaviour impacting on the GBR'. They identify areas of strength and opportunities for improvement including a need for 'stronger partnership and trust building' and 'the development of stable and long-term institutions for catchment scale action' (p. 11).

The innovation processes are driven by political power dynamics that influence the philosophies, approaches and processes used to drive behaviour change (de Boon et al. 2022; Cronin et al. 2024) through the use of norms, such as explicit or implicit understandings about the paradigms to be used when conducting research, development and extension. Critically, perceptions of legitimacy of the governance system and the level of participation of those affected by the innovation processes and their outcomes influence it effectiveness (Dale et al. 2018; Olvera-Garcia & Neil 2020). Uncertainty about context, drivers and outcomes leads to contested knowledge, goals, pathways and responses, so the governance system must allow for diversity and be flexible and adaptable.

Meso-micro system for relevant actors of the GBR agricultural systems

The meso-micro system encompasses the key stakeholders within the main agricultural value chains and the relevant actors from the enabling environment (Macro context of the AIS for the GBR value chains

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Figure 9). In Figure 10 we use the governance framework developed by de Boon et al. (2022). This framework identifies key components for the stakeholders in the meso- micro system (actors' innovative capacity, adaptive capacity, and psychosocial factors). We also draw from the Extension Model of Practice (Williams et al. 2021), the Behaviour Change Wheel (Michie et al. 2011) and Tully's educational process (1966). Our framework describes four interconnected components:

Actors’ innovative & adaptive capacity Innovative and adaptive capacity are combined here since they are determined by many of the same elements (see de Boon et al. 2022, pp. Table 2, p. 412) and interact and influence each other. Innovative and adaptive capacity in the our framework are akin to the dispositional factors that are characterised by Dessart et al. (2019, p. 5) as being 'higher order, general "macro" principles, relatively remote from specific decision-making situations’. They are stable over time yet play an important role in shaping our behaviour.

Actors' knowledge, skills & capacity These are defined as awareness, knowledge, skills, and physical and psychological capacity to change practices (Michie et al. 2011). This component includes the knowledge, skills and capacities of all actors in the AIS for the GBR—from farmers implementing practices, to extensionists scaling solutions, to innovators developing contextually appropriate technologies, to policymakers designing effective programs to improve water quality outcomes for the GBR. Because they have a more direct influence on particular decisions, they are separate from broader adaptive capacity (Dessart et al. 2019).

Actors' institutional and psychosocial context This includes psychological factors (which occur mostly at an individual level) and social factors that influence individuals (but which occur mostly at the family, community and agency level), and formal and informal institutions. Psychological factors are diverse. They include perceived behavioural control, perceived benefits and costs, and perceived risks of an innovation for their farming goals, resources and farming system (Dessart et al. 2019). They also include factors such as descriptive norms (what other people do), injunctive norms (what people think others expect them to do) and signalling or social identity motives (improving image or to be seen as a 'good farmer' or 'good researcher'). The social context also includes the levels of social capital in the farming community or more broadly in the whole system.

Actors' physical & environmental context The physical and environmental context at the meso-micro level includes farm soils, climate, infrastructure, equipment, resources, local environment, and remoteness; public infrastructure (e.g. roads, communications, transportation, irrigation, education, energy) and private infrastructure related to regional industries. It is a sub-set of the natural capital, but the specific context of different communities and industries will influence their ability to adopt or adapt particular innovations, and also influence the processes by which innovations are developed (de Boon et al. 2022).

Innovation processes

A key component of an AIS is the innovation processes that develop and shape the innovations aimed at achieving sustainable impacts for the GBR. As described above, the innovation processes in an AIS involve the learning and development that occurs across the system.

Within the GBR, actors and agencies at the meso and micro level apply innovation processes to develop, refine and spread a suite of innovations. At the core of innovation processes are the explicit and implicit stocks of both technical knowledge, research and innovations (at various stages of development and adoption), and processes used to develop and extend innovations (de Boon et al. 2022). For actors within the system, relevance of technical knowledge, research and innovation will vary with the context.

The early stages of the innovation processes can be highly politicised and set the strategic direction for the innovation processes. Because of this, these processes should be explicitly understood and scrutinized as potential enhancers and barriers to behaviour change (de Boon et al. 2022; Cronin et al. 2024; Metze et al. 2026). Power struggles, due to contested understandings and knowledge about levels and causes of reef water quality between landowners and government bodies, have been critical to change (Coggan et al. 2021a). Building relationships or social capital throughout the GBR AIS is the first stage in the innovation process. Relationships also influence all other innovation stages. Selecting innovation strategies must allow for participation and influence by those who will be involved in implementing the innovation, considering their needs and priorities. In the case of the GBR this is often farmers. Ignoring the needs and priorities of farmers or adopters may lead to inappropriate framing of the problem, which can lead to ‘solutions’ that are perceived as the wrong solutions to the wrong problems.

The fourth stage involves developing concepts or prototypes of innovations. This can range from a farmer using a welder to add an improvement to a piece of machinery, to a group of researchers working on a ‘blue-sky’ solution to reducing herbicide resistance. It is important to note that an innovation might not necessarily involve developing an entirely new management practice; it can also involve developing new processes, methods, or approaches to increase the adoption of already-developed management practices. The next stage is field testing the innovation under the relevant conditions. Innovations may initially be tested in a research setting and then shifted to on-farm; alternatively, other innovations may start on-farm and be adapted to suit the context.

Monitoring and evaluation should be conducted alongside all stages, preferably using participatory processes with all relevant actors. Unfortunately, this stage is often poorly designed, implemented and funded (Coggan et al. 2024; Murray-Prior et al. 2024). As argued by Rickards et al. (2019) and de Boon et al. (2022), monitoring and evaluation can also be a political process. Whoever has the power over this process can determine who is evaluated, what lessons are emphasised, and who is held accountable if they are not satisfied with the outcomes.

Finally there is a need to spread the innovation more widely (de Boon et al. 2022), often referred to as scaling (out and up) to achieve transformational change (Douthwaite et al. 2003; The World Bank 2012; Murray-Prior 2020). Approaches distinguish between: scaling out (spreading within the same stakeholder groups); scaling up (institutional scaling to involve other stakeholders and improve the enabling environment – from micro to macro); and spatial scaling up (from research plot, to field, and then outward to catchment and region) (Douthwaite et al. 2003).

While we describe these distinct model stages, we recognise that in practice, they overlap and interact. Some innovations won't get past the conceptual or prototype stage.

Innovation characteristics

We include the characteristics of the innovations because these have been widely discussed in the literature as factors that enhance or constrain the adoption of innovations (e.g. Rogers & Shoemaker 1971; Guerin & Guerin 1994; Guerin 1999; Pannell et al. 2006; Coggan et al. 2021b). Pannell et al. (2006) combine the five characteristics of Rogers (1995) (relative advantage, compatibility, complexity, trialability, and observability) into two broad categories: relative advantage (which includes relative advantage, compatibility and complexity plus others) and trialability (which includes trialability and observability). Farmer perceptions of these are the key to their adoption, but the processes used to develop the innovations and scale them also influence the perceived characteristics of innovations (e.g. Coggan et al. 2021a). Another distinction is between commercial innovations, which focus on productivity, and environmental innovations, which target environmental improvement. Innovations may also vary in the time lag between adoption and beneficial outcome, where environmental innovations typically have more delayed benefits than commercial innovations (Guerin & Guerin 1994; Pannell et al. 2006; Kealley & Quirk 2016; Coggan et al. 2021b).

Discussion

Contribution of the framework

The framework is a first attempt to link the concepts derived from the extensive literature on AIS with the 'wicked' problem of improving GBR water quality. Viewing it as a system shifts the focus from farmers as the primary unit of change to include all elements of the innovation and governance systems as potential sources of innovation and change. Explicitly addressing all actors within the system recognises power dynamics over the innovation system processes that address the 'what ought to be' questions. With GBR health now considered "very poor", with urgent calls to action (Great Barrier Reef Marine Park Authority 2024), it is time to reframe and embrace the GBR water quality challenge as a 'wicked' problem and apply an AIS approach to design and implement solutions.

By integrating AIS principles with governance analysis, behaviour change theory, and extension theory, the framework presented here offers an integrated diagnostic tool to understand the system. It connects macro governance dynamics to meso and micro level actor capacities and innovation processes relevant to agricultural value chains in the GBR catchments. This integration is significant because it means that factors which are typically examined in isolation (e.g. farmer adoption behaviour, governance structures) can be understood in relation to each other and to the broader system dynamics shaping water quality outcomes.

The framework also helps decision makers to engage with questions related to power and contested knowledge systems. For example, power struggles landowners and government bodies related to contested understandings of reef water quality and its determinants have been critical to change (Coggan et al. 2021a). The framework addresses this by explicitly incorporating power dynamics at the macro governance level and throughout the innovation processes and recognises that whoever controls the monitoring and evaluation process can determine who is evaluated, what lessons are emphasised, and who is held accountable (Rickards et al. 2019; de Boon et al. 2022).

Practical implications

There are numerous practical implications arising from the framework. Before designing regulations, investment or new RD&E programs, policy makers and program designers can use the AIS framework to map and understand the actors, institutions and relationships that should be considered across the relevant value chains and innovation processes. For instance, if it is planned to use regulation to force change, consideration needs to be given to the design and implementation of these regulations so that they do not have unintended consequences for attitudes to change and levels of social capital in the system. Regulations in the past have led to increased levels of distrust, which in turn have led to increased levels of noncooperation with reef programs more generally (Dean et al. 2023). At the project level, the framework could be used to identify the key actors to include, their capacities and contexts and the nature of the innovation process used to design, implement and evaluate practice change along with the actors' perceptions of characteristics of the practices.

Limitations

A legitimate concern with any systems framework is whether it is manageable in practice. Policy makers and program designers, who work under real institutional and resource constraints, cannot address all elements of the system simultaneously. The AIS framework is not intended to replace existing approaches but to complement them by providing the systems-level lens needed to understand how and where those approaches can be applied most effectively, and how they interact as part of the broader innovation system. For instance, a practitioner might focus primarily on the meso-micro actor capacities and innovation processes most relevant to their situation, using the macro governance layer as background understanding rather than an active focus of intervention.

A further limitation is that while the framework identifies a wide range of enabling and constraining factors, it does not prescribe how to empirically operationalise or prioritise them. That depends on context, available resources and process. While the framework was used to support the evidence synthesis for the 2022 SCS, it has not yet been formally applied or empirically tested in a program or project design context. However, AIS frameworks have been widely applied and tested in international development contexts. Empirical application and testing across different GBR catchment contexts and value chains is therefore an important priority for future research.

Conclusion

This paper has developed the first AIS framework specifically designed to address the 'wicked' problem of improving water quality in GBR catchments. Its conceptual contribution lies in integrating AIS principles with governance analysis, behaviour change theory, and extension theory into a unified diagnostic tool that operates across macro, meso and micro levels of the system.

The practical value of the framework lies in its ability to help policy makers, program designers and researchers see the full system before intervening in it. If used before designing regulations or investment programs, it can help map the actors and relationships that matter and diagnose the governance and innovation processes most likely to enable or constrain the intended change. Applying this framework may help avoid patterns of well-intentioned investments that address only part of the problem and consequently fall short of intended targets and impact.

Empirical testing of the framework is the most important priority for future research. This includes developing practical tools to help users prioritise intervention points and building a more consistent evidence base on the factors enabling and constraining practice change and addressing one of the key weaknesses in the current research landscape identified in the 2022 SCS. With GBR health now considered "very poor", the need for a systems-level approach to research, policy and program design has never been more urgent.

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