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Impact and strain monitoring in glass fiber reinforced epoxy laminates with embedded Quantum Resistive Sensors (QRSs)

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ABSTRACT

The use of composite materials in large structures such as wind turbine blades, proposed as a renewable energy solution, is currently increasing. Due to their expected lifetime, they may be subjected to a variety of punctual damaging events, such as impacts. The extent of damage caused by impacts can range from weak (rain) to locally destructive (birds). Detecting and locating these impacts could help assess the health of the part, monitor its state and could lead to a better prediction of its ultimate failure, thus reducing maintenance cost, within a broader framework of structural health monitoring. Here, we studied the use of Quantum Resistive Sensors (QRSs) for the detection and localisation of impacts that could be whether hail, bird or maintenance tool impacts occurring on an epoxy-glass fibre laminate. At an acquisition frequency of 4800 Hz, the electrical behaviour of QRSs was found to be simultaneous with the impact load. The use of multiple sensors within and between plies further evidenced that the change in resistance is proportional to the impact energy and could help to locate the impact area. The effect of repeated impacts on the electrical properties of the QRSs was then studied. With the accumulation of impacts that have reduced Young's modulus of the sample, both the resistance at rest and the amplitude of the response during dynamic cycle increased. Therefore, QRSs could provide an in situ probe in composites to detect, localize, quantify the

energy of an impact to anticipate the resulting drops in mechanical properties of the composite.

KEYWORDS

Carbon nanotubes, GFRP, nanocomposites, Impact monitoring, SHM.

1. INTRODUCTION

Broadly the use of renewable energy sources is presented as a way to adapt to climate change while mitigating greenhouse gas emissions in developed and developing countries.

Renewable energy from resources such as wind, solar, hydroelectric, tidal and geothermal offers an alternative to conventional energy. They are considered as a key element of the European energy policy to possibly cover a large part of the energy needs of the European Union [1]. Beyond the discussions on the high installation costs, they could reduce the dependence of countries on energy imports (e.g. fossil fuels), increase the security of energy supply and achieve the objectives of reducing carbon emissions and ensuring environmental protection. For this it is important to understand and assess the environmental impacts in order to integrate these considerations into the design process [2,3]. In 2015, COP 21 agreed to achieve a balance between carbon emissions and the removals of greenhouse gases by sinks [4]. This current interest in renewable energies is not episodic but expresses the desire to include them more and more in the global energy mix. The French environmental agency, ADEME, has estimated that in 2050, an electricity mix including only renewable energies could be economically more sustainable than all other existing proposals [5]. Wind energy was recognized as an interesting solution very early on. Many rapid developments have been made to increase the efficiency and power capacity of wind turbines. The low operating cost and high availability of wind power has made it one of the most advantageous and efficient sources of renewable energy [6,7]. In France, for instance it is planned to increase *on-shore* wind farms from 9.3 GW (2014) to 26 GW (2023) and to develop *off-shore* wind farms up to 3 GW in 2023 [8].

To keep up with this growth in wind energy, the power rate as well as the size of wind turbines is constantly evolving [9]. Modern technological developments are focused on optimizing a turbine and its components for a significant improvement of the generated power

and efficiency. In the early 1980s, the length of the blade was 7.5 m, whereas it is 80 m today, and could exceed 100 m in 2030 [6,7]. To ensure a continuous and powerful wind flow, the turbines are designed for a harsher environment, and located further offshore from the coast [10]. An important point is the improvement of the life span of these parts, with an interest in limiting or optimizing the maintenance phases (and costs) that are scheduled rather than anticipated. Nowadays, composites materials are indispensable for the manufacture of wind turbines blades, typically made of glass fibres assembled with an epoxy matrix [11] .

However, composites are anisotropic or orthotropic materials, and their failure is a combination of various mechanisms such as matrix cracking, delamination, fibre breakage, or interfacial debonding [12]. As a result, the initiation and propagation of damage remains difficult to predict.

During its 20-year life, the blade of a wind turbine can be subjected to different types of events, including various load levels but also impacts. These impacts are mainly due to the weather conditions, rain, hail, lightning, and even to the collision with bats [13] or birds [14]. In France, the number of collisions per year between birds and wind turbine has been estimated at 2.15 per wind turbine with a bird mass ranging from a few grams (Goldcrest) to more than one kilogram (Red kite). These different events result in a wide range of impact energy, from 10^{-6} J, in the case of rain for example, to hundreds of joules for birds and hail, as shown in Figure 1.

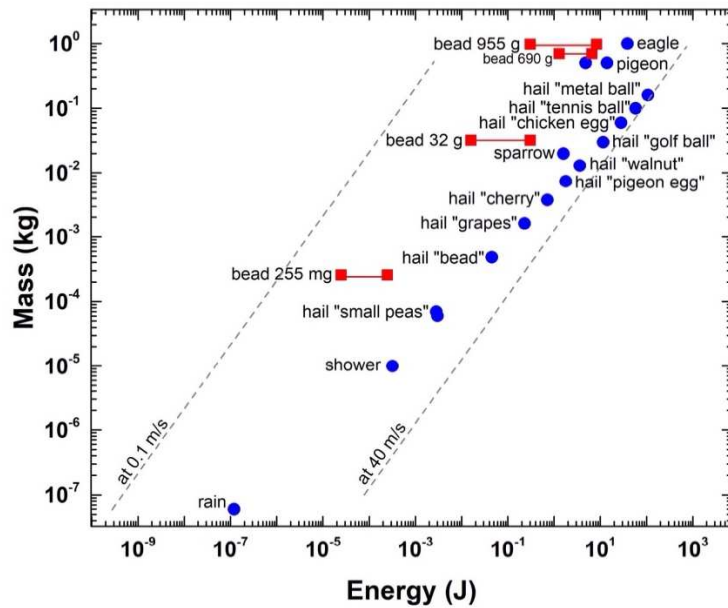


Figure 1: Map of the mass and energy of various projectiles (blue circles symbols), including birds and atmospheric precipitation [15,16]. Representative steel beads of varying diameter and mass (red squared symbols) were used to simulate an external projectile during impact measurements at two different velocities. The dashed lines indicate the energy values of the projectiles considered assuming an impact velocity of 0.1 m/s or 40 m/s.

A single or repeated impacts throughout the life of the structure may induce irreversible local damages. Depending on their location and intensity, these impacts can cause defects and cracks, weakening the part by greatly reducing the native properties of the composite laminate. Detecting these impacts in addition to a deformation monitoring system could thus promote a better prediction of the ultimate failure of the structure, resulting in reduced maintenance cost. Currently, the main non-destructive testing techniques, such as ultrasound, acoustic emission or X-rays [17], require complex, impractical or time-consuming equipment to locate and estimate the amount of damage to a composite part in use, despite the wealth of information they provide on the behavior of the material under the various stresses encountered. It should be noted that the FTIR technique [18,19], recently applied to thermoplastic or thermoset composites, allows to obtain relevant information on the

understanding of the behaviour under impact, but it is considered as a non-destructive analysis technique which is not or not directly applicable as a monitoring solution in use for composite parts. In recent years, carbon nanotubes (CNTs) have opened an additional approach to measuring strain and damage in composites structures. Thanks to their outstanding electrical [20,21], thermal [22,23] and mechanical properties [21,24], they are one of the main candidates for the development of nano-composites. In 2004, DHARAP *et al.* [25,26] were the first to use the electrical properties of CNTs to develop a strain sensing device using a dense network of CNTs. The sizing of reinforcement fibres with CNTs [27,28] and the dispersion of CNTs within the polymer matrix [29–32] have proven to be alternative strain sensing techniques. THOSTENSON and CHOU [29,31,33–40] additionally found that the electrical resistance of CNT networks was sensitive to damage accumulation in composites. In the same research team, MURRAY *et al.* [41] recently demonstrated that using an industrially scalable electrophoretic deposition technique, the addition of carbon nanotubes directly on the reinforcing E-glass fabric the damage state can be identified. They furthermore indicated that the carbon nanotubes therefore located at the fiber/matrix interface could even prevent crack growth by introducing a tough interphase around the fiber. To enable the detection of local events with a shorter computing time, FELLER *et al.* [42,43] locally filled the matrix with CNTs to form a Quantum Resistive Sensor (QRS) and monitored the electrical resistance to detect local strain and damage accumulation in the core of the carbon fiber reinforced epoxy sample during static and dynamic tests. **In addition, QRSs did not deteriorate the mechanical properties of the composite sample [42,44,45]. QRSs are developed as sensing patches obtained by layer-by-layer (sLbL) sputtering of CNT-epoxy solutions onto a microcomposite substrate [46]. The dimensions of the transducer as well as the design of the electrodes can be tailored "on demand" to the desired configuration in the host thermoset-based structural composite. These so-called quantum resistive sensors (QRSs) can be fabricated from the same**

resin as the composite and cured to the same level of crosslinking to ensure complete homogeneity of thermal and mechanical properties. Conveniently, the resulting strain sensitivity (gauge factor, GF) can be adjusted by changing the composition or processing conditions [44,47]. Finally, QRSs derive their high sensitivity to their environment, and in particular to nanodeformations, from the percolated nature of their sensing architecture favoring tunneling conduction at the expense of classical ohmic conduction, which tends to produce an exponential variation of the resistive response when the interparticle distance increases, as described and used by several authors [48,49]. Wang et al. have used a modified model based on tunnelling theory to describe the relative change in resistance as a function of applied stress in highly sensitive thermoplastic-based systems [50]. Garcia et al. lately showed the effect of strain on the particle network to be at least as important as the effect of strain on the interparticle resistance [51]. Recently Lemartinel *et al.* [45] demonstrated the ‘in plane’ and ‘through thickness’ monitoring of strain using an array of QRSs embedded in epoxy-carbon fiber laminates that were subjected to static and dynamic cycling bending loads. The results showed that the amplitude of the electrical signal, which appears to be very fast, agreed with the induced deformation field, i.e., proportional to the distance of the loading span but also as a function of the depth (position of the ply) within the composite part, suggesting the ability to map the deformation field by placing several QRSs within the specimen. The use of localized addition of CNTs therefore appears to be a potential technique for detecting brief and punctual events. In continuation of this work, the present study focuses and reports on the electrical behaviour of the QRSs implemented in the core of the glass fiber reinforced epoxy laminate subjected to various impacts. During the test, the influence of the induced deformation field and the impact energy on the recorded electrical signal will be studied. Then, the use of QRSs resistance as a witness of the accumulation of damage in the

sample will be investigated to explore whether it can be used as adjunctive component for a SHM solution.

2. EXPERIMENTAL DETAILS

2.1. Materials

The multiwall carbon nanotubes (NC-7000 MWCNT) were kindly provided by Nanocyl (Belgium). This grade corresponds to MWCNTs with an average diameter of 9.5 nm and a mean length 1.5 μm . Epolam 2020 epoxy resin and amine hardener were purchased from Axson, France. Chloroform (99 %) was purchased from Sigma-Aldrich (France) and Taffetas E-glass fibre ($0^\circ/90^\circ$, 165 gm.m^{-2}) from Gazechim France.

2.2. Fabrication of samples

4 mg of CNTs and 150 mg epoxy resin were homogenized in chloroform by ultra-sonication with a Branson 3510 sonicator for 6 hours at 25 C, and then degassed for 5 minutes. After dispersion of the CNTs in the epoxy resin, 50 mg of amine hardener was added, and the mixture was then sonicated for 5 minutes. Sensors in the form of a 1 cm x 0.5 cm thin film (approx. 10 microns for the active area) were obtained by spray layer-by-layer (sLbL) deposition technique [42]. The solutions were sprayed with our homemade device allowing precise control of nozzle sweep speed (10 cm s^{-1}), solution flow rate (50 mm.s^{-1}), stream pressure (0.20 MPa), and distance between target and nozzle (10 cm). The QRSs were then subjected to the curing cycle of epolam 2020: 4 h at 25 °C, 2 h at 60 °C, 2 h at 80 °C and 2 h at 120 °C with a temperature rate of 40 °C/h. QRS integration was then carried out during the composite stacking sequence via a thin glass-epoxy substrate (130 microns), followed by the final 4-mm thick laminate cure cycle. Connections to record QRSs electrical resistance were made with silver ink added before spraying.

2.3. Characterization techniques

Impact tests were conducted on an Instron Datup 8250 drop-weight impact test machine. In order to reproduce an equivalent range of drop impacts on epoxy-glass fibre composites, several metal balls of varying diameter and mass were selected (255 mg, 32 g, 690g and 955 g for 3.9 mm, 20 mm, 75 mm and 26 mm, respectively), as shown in Figure 1. Their resulting energy range matches with rain for the lightest bead, to 3 cm diameter hail or birds (such as pigeons) for the heavier beads, **also depending on the velocity related to the height of the free fall. For the single impact study, the impact ball used was 26 mm in diameter and 955 g in mass, giving access to energies of 0.31 J to 8.4 J for respective fall velocities of 0.8 to 4.2 m/s.** Six QRSs were embedded into the sample at several locations, as shown in Figure 2.a. Thus, depending on their location and during the impact test, the sensors are supposed to express the different deformations experienced, from compression to tension, under the affected area and outside the impact [45]. In the case of repeated impacts, a QRS was incorporated on the side where the specimen is loaded in tension during the cycling and impacts tests, as shown in Figure 2.b, and the impact bead used weighed 690 g. An Instron Electropuls E10000 was used to perform dynamic three-point bending experiments at 2 Hz with a maximum strain of 0.1 %. The experiments were performed at room temperature (23°C) and relative humidity (48%). In the repeated impact experiments, 300 cycles were run between two consecutive impacts to evaluate the electrical properties of the QRSs (i.e., strain sensing ability) and the Young's modulus of the sample. The resistance measurement was performed by a QuantumX MX 840A from HBM. The electrical response is represented by the relative amplitude of the electrical resistance (A_r), being the ratio of $\Delta R/R_0$, where ΔR is the change of electrical resistance compared to R_0 is the initial resistance at rest. To ensure the measurement of the rapid impact, *i.e.*, 1 to 3 ms, the acquisition frequency was set at 4800 Hz

when measuring the impact. During the fatigue testing, the acquisition frequency was set at 20 Hz. The JEOL JSM-6031F has been used for Scanning Electron Microscope measurements.

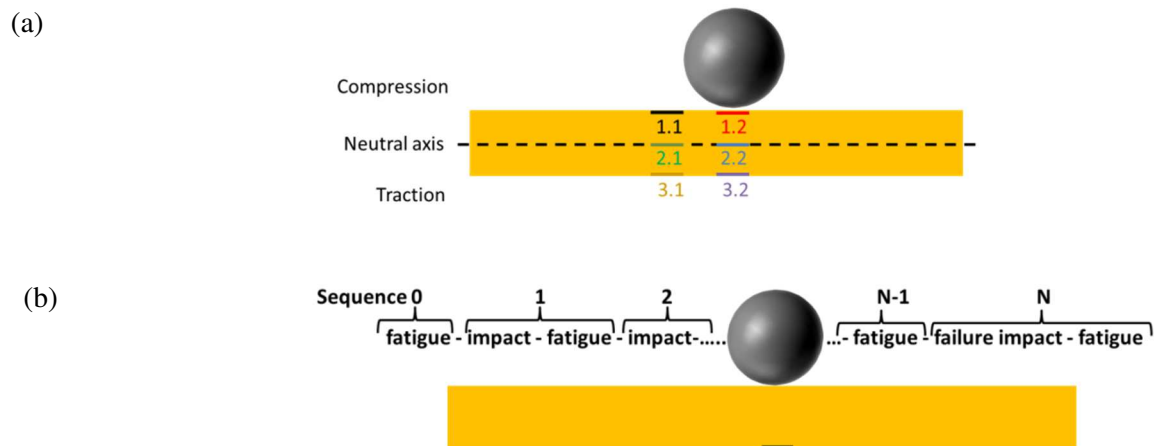


Figure 2: Impact tests with a spherical indent on the epoxy-glass fibre composite equipped with QRSs. (a) In the case of a single impact with six QRSs, position of the QRSs in compression (QRS#1.1 and #1.2), tension sides (QRS#3.1 and #3.2), neutral axis (QRS#2.1 and #2.2), and under the bead QRS#x.2 or on the side of the sample QRS#x.1. (b) In the case of repeated impacts, test sequence and schematic representation of the specimen with the QRS positioned in the tensile side for both fatigue and impact.

3. RESULTS AND DISCUSSION

3.1. Electrical behavior of several QRSs integrated through the thickness and subjected to a single impact

First, to observe the electrical response and the effect of the deformation field on the specimen upon impact, 6 QRSs were positioned at different locations in the epoxy-fiberglass composite specimen as shown in Figure 2.a. Typical electrical (A_R) and mechanical responses of the QRSs and load are shown in Figure 3.a under an impact energy of 0.31 J induced by the 26 mm diameter bead (955 g).

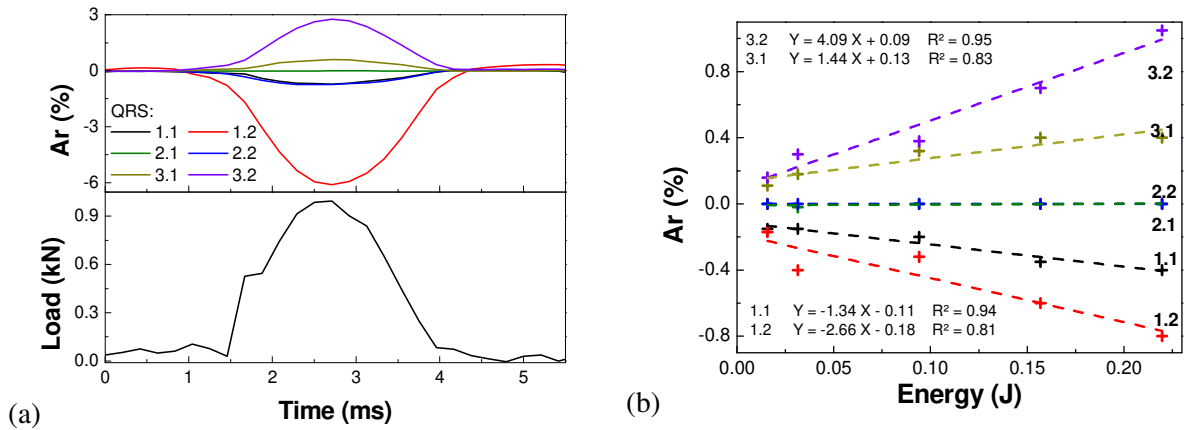


Figure 3: (a) Typical electrical and load response of the 6 QRSs on a 0.31 J impact (induced by the 26 mm diameter bead **with a mass of 955 g**). (b) Maximum change in the resistance of the 6 QRSs with the initial energy of the balls for low energy impacts (non-damaging).

The load curve is similar to previous observations for the composite material in the absence of damage in the specimen [52,53]. **As a remark and considering the period between two measurements, the QRS response time is estimated to be less than 0.5 ms.** From an electrical point of view, the response of the QRS is in phase with the load, i.e., its intensity and type. The magnitude of the response depends on the vicinity of the sensor to the impact area. Indeed, three QRSs show a negative change in resistance, i.e., QRS#1.1, QRS#1.2 and QRS#2.2, one has neutral response, i.e. QRS#2.1, and two have a positive change of resistance, i.e. QRS#3.1 and QRS#3.2. These responses are expected since QRS#1.1 and QRS#1.2 are on the compressed side, QRS#2.1 is in the neutral axis, and QRS#3.1 and QRS#3.2 are on the side experiencing tension. These observations are consistent with our previous study [45]. Although QRS#2.2 is assumed to be on the neutral axis, the negative change in resistance suggests that the QRS was actually under compression because of a local decrease in specimen thickness below the vertical axis of the ball (e.g., imperfect positioning of sensors during the manufacture of the laminated composite). This slight imperfection in the strict positioning of the sensors also explains the not fully symmetrical response of QRS#1.2

and QRS#3.2 on the compression and traction side, respectively. In addition, QRS#1.2 and QRS#3.2 which are placed under the impact, exhibit a maximum change in resistance approximately 6 times higher than the QRS#1.1 and QRS#3.1 (on the side of the sample). This observation is again consistent with the strain expected to be experienced upon impact [45]. The influence of location on the maximal change in resistance is clearly illustrated in **Figure 3.b**. The maximum electrical signal from the sensors, A_r , is displayed as a function of the (low) impact energy of the balls and their location. For all sensor positions, and within this limited energy range, the maximum A_r appears to vary linearly with energy. This increase in A_r is consistent with the increase in the stress implied by the impactor speed [54]. For a higher range of velocity and energy, Steinke et al. [55] also found a direct relationship between projectile velocity and the change in impedance of their laser induced graphene sensing layer in an aramid-resin composite. It can therefore be noted that if one considers a mesh (or an array) of QRSs in a specific area subjected to an impact, a faithful description of the induced deformation field is possible. It should be noted that the number, the location, the spacing of the sensors between them, and even the mode of interrogation of the sensors are crucial parameters as specified by some authors who have developed relevant optimizations[56,57]. Ideally, QRSs could be used as integrated sensors to detect, locate and estimate the energy of an impact on a composite part.

In addition to the non-damaging tests, destructive impacts were performed using the same sample configuration. **The specimen was exposed to impact of 4.7 J (induced by the 26 mm diameter bead, 955 g, at a velocity of 3.14 m/s). The damages are visible in Figure 4, which is a postmortem SEM picture of a section of the sample. The area affected by the impact is conical in shape, with a minimal affected area under the impact and a maximal area on the**

traction side.

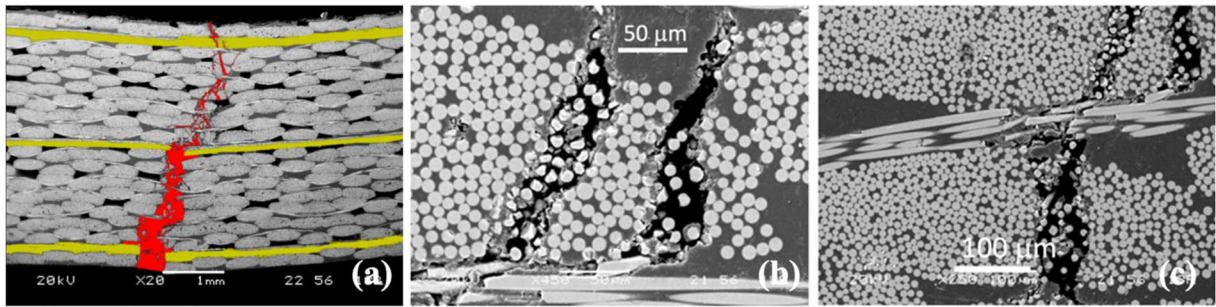


Figure 4: Transversal SEM observation of the impact sample 4.7 J. (a) Overall view with the fracture coloured red and the QRS films coloured yellow. Focus on (b) matrix cracking, fibre/matrix decohesion and (c) transversal fibres cracking.

Figure 5 displays the mechanical and electrical responses of the sample and QRSs upon a destructive impact of 4.7 J. Regarding the mechanical response, a first load rise is visible after 2 ms. At 3 ms (marker 1), the load drops abruptly, corresponding to the appearance of matrix cracks, fibres/matrix decohesion, delamination and transversal fibres cracks [58–60].

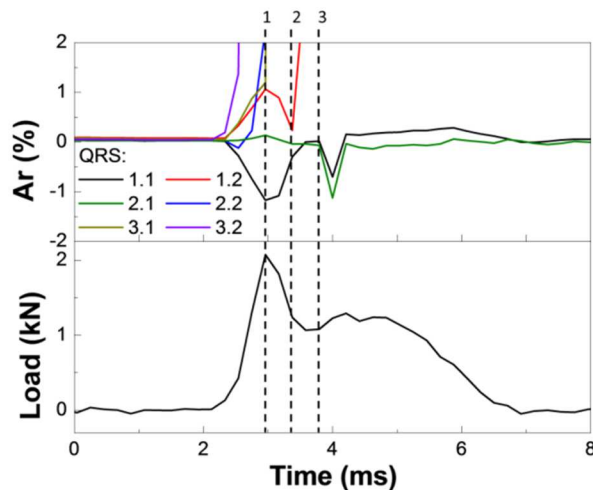


Figure 5: Electrical and mechanical response of the QRSs and the specimen during a destructive impact of 4.7 J with the 26 mm diameter (955 g) ball.

After 3 ms (marker 2), a slight increase in load occurs again. The breakage of the sample leads to singular electrical behaviours of the QRSs depending on their location.

Simultaneously with the first increase in load, QRS#3.2 shows an infinite change in

resistance, which corresponds to the fact that this QRS is in the most damaged area of the sample. QRS#2.2 initially exhibits a decrease in resistance as shown in Figure 3.b, but 0.6 ms after the start of the impact, the infinite change in resistance corresponds to the break-up of one ply of the laminated composite. QRS#3.2 also presents an infinite change in resistance, which occurs at the same time as sample breakage (marker 1). Although the latter QRS is less than 1 cm from the impact zone, the shock wave may affect an area larger than the fracture zone and cause local degradation of the sample. In the case of the QRS#1.2, unlike the previous responses, a positive initial A_r is displayed. Local degradations may overcome the compression effect. An infinite rise is also visible (marker 2), suggesting that the fracture crosses the entire sample below the impact. The two others, i.e., QRS#2.1 and QRS#2.1, show a similar electrical behaviour with the load up to marker 3, as in Figure 3.b. Then the slight reload of the sample occurs simultaneously with a decrease in resistance of both sensors. At this stage, both QRSs are subjected to compressive deformation. The propagation of the damage therefore changed the strain field in the specimen, and the previous neutral axis is at this time on the compression side. Mapping the surface and through the thickness of the sample with QRSs thus provides information on the propagation of damage in the sample during impact.

3.2. QRS response in the case of repeated impacts on the composite part

As stated, earlier in the text, wind turbine structures can be subject to recurring impacts of different speeds and masses. Although not every impact is destructive, the accumulation of damage can lead to structural failure. In order to investigate on the robustness of the QRS during punctual repeated impacts, one sensor was embedded under the first ply of an epoxy-glass fibre specimen. The ball was chosen to simulate the impact of a bird on the specimen. Thus, the following sequences were repeatedly applied, namely 300 bending cycles with a strain amplitude of 0.1%, representing non-damaging conditions, followed by an impact

related to the drop of a 690 g ball falling from a height of 20, 30, 50 and 100 cm (equivalent to 1.3, 2, 3.3 and 6.7 J respectively), representing damaging events (see illustration in Figure 2.b).

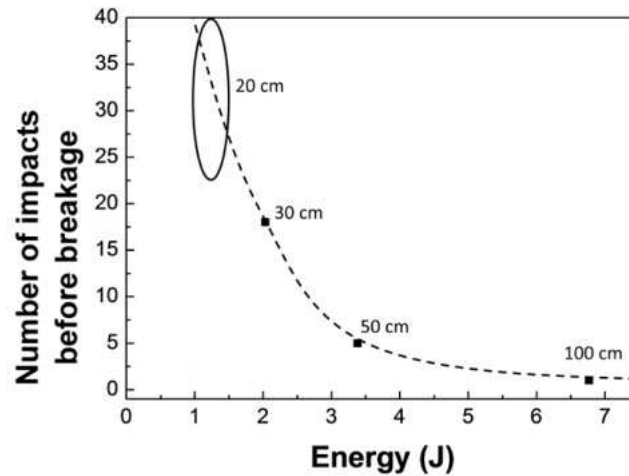


Figure 6: Number of impacts prior to sample rupture compared to the energy of a single impact. Each sample was subjected to a short non-damaging period (300 cycles) with a strain of 0.1 % followed by a drop impact. The sequence was repeated until the laminate fractured. The sample with a drop height of 20 cm (1.3 J) did not suffer any final breakage after 20 drops.

The QRS was positioned so as to be subjected to tensile deformation during cyclic bending sequences at low strain. Figure 6 exhibits the number of ‘impact/fatigue sequences required before sample breakage (also associated to an infinite electrical resistance value). A clear decrease in the number of impacts required for rupture with increasing impact energy is visible. KHAN *et al.* [61] described the relationship between the number of impacts and impact energy as a power equation:

$$\text{Equation 1} \quad E_{im} = A N_f^{-b}$$

Where E_{im} is the impact energy, N_f is the number of impact until sample breakage, A is the energy required for the breakage after one impact and b is a parameter depending on the material.

The maximum of accumulated energy is therefore dependant on the impact energy, and the resulting evolution of the mechanical and electrical properties may differ with in impact energy. SUGUN *et al.* [62] have studied the evolution of the maximum impact load with the number of impacts. They estimated that a constant drop load occurred in the case of glass fibre epoxy composites, which may lead to a constant decrease of the sample mechanical properties. Figure 7.a represents the evolution of the sample Young Modulus with the number of ‘impact/fatigue sequences for different height drops.

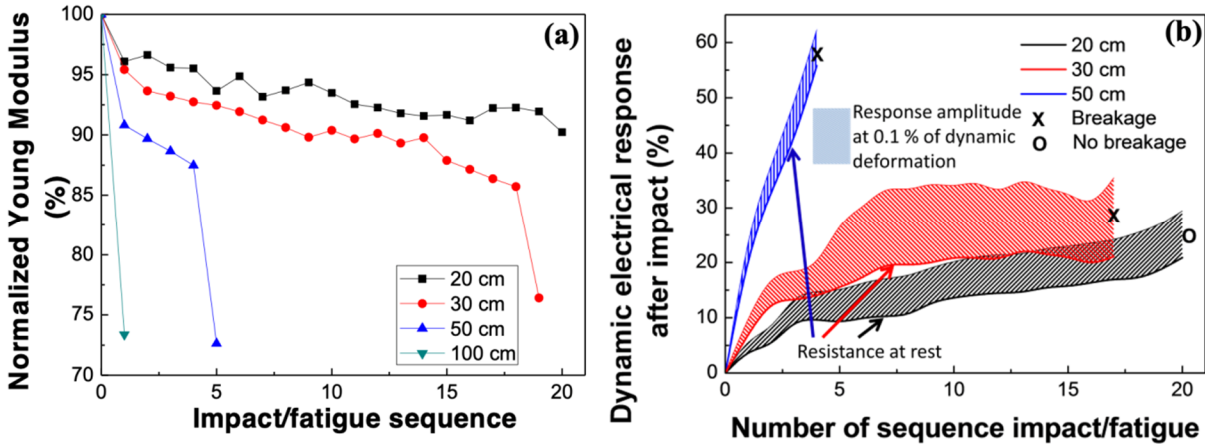


Figure 7: Evolution of the mechanical properties with the number of ‘impact/fatigue’ sequences of (a) the composite and (b) the associated electrical properties of the QRS. The tests were performed with a 690 g ball falling from a height of 20, 30, 50 and 100 cm (equivalent to an energy of 1.3, 2, 3.3 and 6.7 J respectively).

A common behaviour is visible regardless the height of the drop. A first decrease of the Young Modulus occurs after the first impact. This loss increases with the drop height, from 4 % at 20 cm (1.3 J) to more than 25 % at 100 cm (6.7 J), which corresponds to the breakage of the first plies of the sample and therefore the QRS. After the first impact, a nearly linear decrease of the Young Modulus occurs whatever the height of the bead during the drop test, and this until the first plies breakage. Figure 7.b represents the evolution of the electrical behaviour of the QRS as a function of the number of ‘impact/fatigue’ sequences. For each curve, the bottom line is the change in resistance at rest, while the change in the amplitude of the electrical response during the 0.1 % cyclic deformation period is depicted in the

crosshatched area (corresponding to the strain sensing ability of the QRS). Concerning the change of resistance at rest, the trend displayed is opposite to the Young Modulus. Regardless the height, an increase of the electrical signal with the number of sequences occurs. Moreover, the change of resistance is enhanced with the drop height. This corresponds to the increase in damage and cracks in the sample, which results in disconnection and disruption of the conductive nanotube network. As the QRS resistance at rest has been showed to be an indicator of the damage accumulation in static experiments [42], it can also be used in the case of dynamic tests. Furthermore, the amplitude of the electrical response during the 0.1 % cycling deformation is also enhanced by the repeated impacts. Before the first impact, the amplitude is equivalent for all QRSs, about 0.25 %, while after the third sequence it becomes 4.9 %, 4.8 % and 3.1 % **50-, 30-, and 20-cm drops, respectively**. This increase of the sensitivity towards the strain deformation during the cyclic bending period results from the appearance of cracks in the specimen, as for the resistance at rest. During the mechanical deformation, the opening of cracks promotes the disconnection of electrical paths in the carbon nanotubes network, which leads to a larger change in resistance. Therefore, the resistance at rest and the amplitude of the electrical response have both a specific evolution depending on the number of impacts and the height of the impact load. When embedded into a composite wind blade, both resistance drift and electrical amplitude change during a specific deformation could be indicators of the level of impact damage in the area monitored by the QRS. The integration and monitoring of QRS electrical resistance at predefined locations and within the thickness of a laminate composite could therefore provide in situ information on the health of the structure in the general context of SHM.

4. CONCLUSION

As composite structures, such as wind turbines, increase in size combined with their expected life span, the occurrence of damaging events, such as impacts from hail or birds, is inevitable.

First, the present paper focuses on the electrical behaviour of CNT-based nanocomposites sensors, namely QRS, embedded in a GFRP sample subjected to impacts of different intensity. During a 4800-Hz acquisition, the QRS response was in phase with the impact load. This therefore demonstrates the ability of QRSs to detect short events of less than 5 ms with a simultaneous response to the applied load. Second, mapping the sample with multiple QRSs along the surface and through the thickness of a layered composite revealed that each QRS has a unique electrical behavior based on the local strain field (compression, tension, neutral axis, and impact distance). QRSs have therefore demonstrated the ability to make through thickness measurements and that a mapping of QRSs would provide the impact localisation. Third, the maximum change in QRS resistance was found to be linear with impact energy. Therefore, the electrical behavior of the QRS can quantify impact energy, ranging from hail to bird in our study. Finally, QRSs were subjected to repeated impacts interspersed with elastic deformation by cycling. The drift of the electrical resistance at rest, as well as the increase in resistance amplitude during cycling showed that the QRS signal is indicative of local damage accumulation and change in the mechanical properties of the sample. QRSs have thus demonstrated their ability to provide a measurement in the thickness of a laminate and that a mapping by the use of several QRSs would allow, if necessary, to locate the impact and notify of the state of health of the specimen in order to avoid a catastrophic failure.

5. CREDIT AUTHOR STATEMENT

Conceptualization, M.C., J.-F.F.; methodology, A.L., M.C., J.-F.F.; validation, A.L., M.C., J.-F.F., O.F.; formal analysis, A.L., M.C., J.-F.F.; investigation, A.L., M.C., J.-F.F.; resources M.C., J.-F.F.; writing—original draft preparation, A.L.; writing—review and editing, A.L., M.C., J.-F.F.; visualization, A.L., M.C., J.-F.F.; supervision, M.C.; project administration, O.F., J.-C.D.L., J.-F.F.; funding acquisition, J.-C.D.L., J.-F.F. All authors have read and agreed to the published version of the manuscript.

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1 1. Introduction

2

3 Improving the water quality entering the Great Barrier Reef (GBR) is urgent for policymakers at the
4 state and federal level in Australia (Commonwealth and Queensland Government, 2018a). Coral reef
5 ecosystems occur in relatively oligotrophic (nutrient poor) waters, and eutrophication (nutrient
6 enrichment) threatens their persistence through reduced photosynthesis, increases in competitive
7 benthic species (e.g., macroalgae), increases in rates of disease, and outbreaks of coral predators (e.g.,
8 crown-of-thorns starfish) (MacNeil et al., 2019). Scientists have known of sediment and nutrient run-
9 off for several decades (Brodie et al., 2012), though only in the last twenty years have regulatory and
10 other policy levers been utilised to address the causes (Brodie and Pearson, 2016). Sugarcane farming
11 is (and has been) the dominant cropping land use in several key catchment areas of the GBR, while beef
12 grazing dominates in others (Waterhouse et al., 2012). Historically these lands have been poorly
13 managed from an environmental perspective and current efforts from both industry and government,
14 whilst encouraging, are failing to reverse the water quality trends (Waterhouse et al., 2017; Brodie et
15 al., 2019; Commonwealth and Queensland Government, 2019; Great Barrier Reef Marine Park
16 Authority, 2019b).

17 In this paper we consider the role of regulation as an ‘intervention strategy’ (Gunningham, 2011)
18 in the ongoing debate about governing land use in the catchment of the GBR. To explore the role of
19 regulation, we give examples of legislative frameworks that have targeted the impacts of beef grazing
20 (specifically vegetation clearing) and sugarcane cultivation (specifically nitrogen and phosphorus
21 runoff). Recent published work relating to the GBR has focussed on the scientific impacts of agriculture
22 on water quality (Brodie et al., 2012; Waterhouse et al., 2017), climate change and coral bleaching
23 (Hughes et al., 2015; 2017), and the polycentric nature of governance arrangements (Morrison, 2017).
24 This paper contributes to the growing body of GBR work by examining the topic of regulation, which
25 we define as the establishment of rules of conduct and the subsequent monitoring and enforcement
26 of those rules, primarily by the state (Levi-Faur, 2011).

27 There is a growing focus on environmental regulation, including self and co-regulation models as
28 part of the broader governance literature (Eijlander, 2005; Jordana and Levi-Faur, 2004; Gunningham,
29 2009), including in relation to agricultural land use in Queensland (Simmons et al. 2018; Hamman and
30 Deane, 2018; Deane et al., 2018). The examination of water quality is also topical as it provides ‘the
31 strongest management-related predictor of both [GBR] resistance and recovery’ (MacNeil et al., 2019,
32 p. 623). It is also reported as one of the few local-scale coral reef management actions that can achieve
33 positive outcomes in a warming climate (Morrison et al., 2019).

1 This paper is based on a desk-top analysis of regulatory practices in the GBR catchment by
2 explaining the historical issues and industry cultures and using regulatory theory. The paper is
3 structured in four parts. Following this introduction, part two outlines the ecological significance of the
4 GBR and the historical and current state of water quality entering the ecosystem. Here we describe the
5 significance of the GBR's catchment's sheer size and explain the dominant land uses in the region.
6 Recent estimates and future forecasts are provided with the overarching point made that a 'business
7 as usual' approach is unlikely to reverse water quality trends anytime soon (Waterhouse et al., 2017;
8 Eberhard et al., 2017; Brodie et al., 2019). In part three, we canvass past and current approaches to
9 managing land use across the GBR catchment. A brief synopsis of the jurisdictions, institutions and laws
10 relevant to managing the site is provided. Part four analyses the regulatory interventions enacted by
11 the Queensland Government which seek to control (and facilitate) land use and management practices
12 through legislative regimes within the catchment. The suite of regulatory interventions is broad, ranging
13 from planning and major project legislation to water resource management, nature conservation,
14 waste recycling and point source pollution. To focus our analysis, we examine how the environmental
15 impacts of sugarcane and beef grazing are currently regulated in Queensland. This part (and the two
16 that precede it) is important to underpin our analysis as it draws on the unique circumstances
17 surrounding the regulation of agriculture in the GBR catchment. Finally, in part five, we engage in a
18 broader discussion of regulation and question its place in the multiscale governance architecture for
19 the GBR. To deepen the discussion and probe areas for future empirical research, we turn to theoretical
20 concepts from the regulatory literature (e.g. Baldwin and Black 2008; Hutter 2005; Gunningham 2011;
21 Haines 2017; Gunningham et al., 1998; Sinclair 1997; Ayres and Braithwaite 1992). We tentatively
22 conclude that regulation (and state enforcement of it) is a necessary, though on its own insufficient,
23 component of the GBR policy mix when the attitudinal settings of GBR regulated industries are taken
24 into account. We also suggest that catchment regulation must be risk-based and responsive, supported
25 by state-federal collaboration and evaluated against long-term desired outcomes (see also Yoder et al.,
26 2020).

27 2. The GBR, Water Quality and the Catchment

28

29 2.1 *Ecological and socio-economic significance*

30

31 The GBR is one of the most ecologically important coral systems on earth. The 'reef,' as it is
32 colloquially known, (and as used to designate the Great Barrier Reef World Heritage Area (GBRWHA))
33 is comprised of approximately 3,000 individual reefs, including some 1,000 islands, and numerous cays,
34 sandy beaches and rocky outcrops (e.g. Day, 2018). The GBRWHA supports many iconic species (many

1 of which are in an endangered state), such as dugongs, turtles, whales, dolphins and large fish as well
2 as large areas of seagrass meadows. The World Heritage area encompasses 348,000 km², traversing
3 2,300km along the north-east coast of Australia (Hopley et al., 2007). The broader catchment of the
4 GBR is predominately under the jurisdiction of the Queensland state government. The size of the
5 catchment is larger than the World Heritage area and covers approximately 424,000 km² across 35
6 major basins (Brodie et al., 2019). The middle and northern coastal catchments (the Wet Tropics)
7 receive some of the highest rainfall in Australia, while all areas of the GBR catchment are subject to
8 occasional intense rainfall events which lead to flooding and large river discharge events.

9 In addition to its size and ecological complexity, the GBR is a tremendous economic driver for
10 the Australian and Queensland economies. The marine ecosystem supports approximately 64,000 full-
11 time jobs (Deloitte Access Economics, 2017, p. 5), and, in 2015-2016, generated an estimated \$6.4
12 billion in value to the Australian economy (Deloitte Access Economics, 2017, p. 5). Most of the jobs are
13 in tourism (Deloitte Access Economics, 2017, p. 7) and the site welcomes over two million visitors a
14 year, many of them international (Great Barrier Reef Marine Park Authority, 2019c). Aside from the
15 economic considerations, the GBR is also immensely important for Australia's First Peoples (Great
16 Barrier Reef Marine Park Authority, 2019a). Over 70 Aboriginal and Torres Strait Islander groups have
17 a close connection with the GBR and its vast natural resources (Great Barrier Reef Marine Park
18 Authority, 2019a). Since the introduction of the Native Title regime in 1993, following the historic High
19 Court decision of *Mabo v the State of Queensland*, there have been over a dozen separate native title
20 claims within or adjacent to the GBR, including several recent sea claims (National Native Title Tribunal
21 2021). Therefore, the GBR represents a vast area of economic, cultural and environmental significance
22 unmatched in the Australian landscape. Its preservation is a matter that extends well beyond the
23 Queensland state border.

24 **2.2 Declines in water quality**

25

26 Scientists and policymakers have known for many years that the GBR is in decline. This decline
27 has been apparent through declining coral cover (De'ath et al., 2012) but evidence from many other
28 aspects and components of the system are indicative of this trend (Great Barrier Reef Marine Park
29 Authority, 2019b). The decline in coral cover has been attributed to a range of factors, the most
30 important of which is climate change and poor water quality (Hughes et al., 2015; Waterhouse et al.,
31 2017). Despite this awareness, the overall decline is continuing, with the 2019 Outlook Report
32 downgrading the 5 year outlook for the system from a rating of "poor" in 2014 (Great Barrier Reef
33 Marine Park Authority, 2014) to "very poor" in 2019 (Great Barrier Reef Marine Park Authority, 2019b).

1 Since the 1850s, but increasingly since the 1970s, there have been large increases in the
2 amount of fine sediment, nutrients and pesticides discharged to the GBR associated with agricultural
3 development in the catchment (Kroon et al., 2012; Waterhouse et al., 2012). This increased fine
4 sediment export from rivers such as the Burdekin River has increased turbidity in inner-shelf waters
5 (Fabricius et al., 2016), hence reducing light penetration that has been associated with seagrass decline
6 (Petus et al., 2014) and the subsequent death of dugong and green turtles (Wooldridge, 2017).
7 Increased nutrient loading, associated with both sugarcane cultivation (nitrate loads) and beef grazing
8 (particulate nitrogen and phosphorus as part of the fine sediment), are likely to be causative factors in
9 the increased frequency of coral-eating Crown-of-thorns Starfish outbreaks in the GBR (Brodie et al.,
10 2017; Fabricius et al., 2010), as well as severe impacts on coral, extensive loss of seagrass and resultant
11 impacts on megafauna such as the dugong (Brodie and Pearson, 2016).

12 Rangeland beef grazing - the regulation of which is discussed further in this paper – is the dominant
13 land use in the region comprising some 80% of the GBR catchment area (Waterhouse et al., 2012).
14 Grazing is particularly prominent in areas such as the Burdekin River basin (Wilkinson et al., 2013a) and
15 has been correlated with increased erosion in riverine and wetland landscapes (Bartley et al., 2018).
16 There is evidence that erosion may be exacerbated by vegetation clearing and the removal of riparian
17 vegetation in landscapes with low pasture cover (Hairsine, 2017; Bainbridge et al., 2018). Moreover,
18 sugarcane cultivation, and the accompanying fertiliser use is strongly related to the discharge of
19 increased loads of nitrate to the GBR (Waterhouse et al., 2012) and greatly increased concentrations of
20 a range of pesticides into the waters of the GBR (O'Brien et al., 2016; Brodie and Landos, 2019). These
21 land uses and management practices have been a part of the GBR catchment area for over 100 years,
22 hence there are both legacy and current environmental impacts for contemporary governance
23 approaches to address.

24

25 **3. Past and Current Approaches to Governance**

26

27 **3.1 *The Governance Architecture for the GBR***

28

29 The governance architecture for managing threats to the GBR presents is a highly complex
30 'polycentric regime' (Morrison et al., 2017; Dale et al., 2013). As Morrison and others (2017, p. 3014)
31 have noted:

1 The [GBR] regime is characterized by a polycentric arrangement that has evolved since 1975
2 through public participation, cooperative state (Queensland) and national (Australian) law,
3 international oversight, and a variety of other multiactor [sic], multilevel relationships.

4 Although the GBR may appear as a ‘highly streamlined’ system (Evans et al., 2014, p. 420),
5 arguably, the multiplicity of relationships has created much of the regulatory confusion and stakeholder
6 conflict in recent years. One might reasonably hypothesise, for instance, that overlapping jurisdictional
7 control between state and federal governments, as well as the boundaries between coastal and marine
8 ecosystems, have driven a polycentric governance regime that has struggled to deliver region-wide
9 action on water quality (Morrison, 2017). Despite early attempts at intergovernmental collaboration,
10 for example, through the 1979 Emerald Agreement (Commonwealth and Queensland Government,
11 1979), and the recent co-achievement of a Strategic Assessment (Australian Government, 2021), there
12 are still many areas of institutional complexity and jurisdictional overlap at the site. These areas include,
13 for example: the management of coastal development (including ports and shipping); the management
14 of fisheries stocks; the conservation of migratory species; the utilisation of underground water
15 resources; the protection of indigenous and non-indigenous heritage and indeed the management of
16 the GBR Marine Park itself.

17 The reasons for the complexity and overlap are largely historical, and of course, political.
18 Australia is a federated nation, with its component states and territories belonging to separate British
19 colonies until 1901. Under the Australian Constitution, the states retain primary responsibility for land
20 and water management (Robins, 2007) although local and federal governments have overlaying
21 interests in matters of local and national environmental significance (Hamman et al 2021). The political
22 relationship between the Commonwealth government and the Queensland state government at the
23 time of the Marine Park listing cannot be ignored. The declaration of the park occurred, in large part,
24 in response to accusations that the Queensland state government was opening the GBR to limestone
25 mining as well as offshore oil exploration (Wright, 2014; Ford, 2011). Concerned scientists and local
26 activists gained traction for the issue at the national level, and the Commonwealth government passed
27 both the *Seas and Submerged Lands Act* (1973) and the *Great Barrier Reef Marine Park Act* (1975) to
28 stymie the Queensland state government’s plans (at the time controlled by the Country Party). Several
29 years later, in 1979, the state and federal governments signed the Emerald Agreement (Commonwealth
30 and Queensland Government, 1979), and confirmed that ‘it was the policies of their respective
31 governments to prohibit any drilling on the reef or any drilling or mining which could damage the reef’
32 (Fraser, 1979, p. 2). The GBR, like other World Heritage sites in Australia (for example the Tasmanian
33 Wilderness and Daintree Wet Tropics), soon became a political battle ground in the midst of state and
34 federal environmental and land use agendas.

1 In addition to the politics, or perhaps because of them, jurisdictionally-complex issues relating
2 to legislative control of coastal waters of the GBR also had to be ironed out. This was principally
3 achieved through the passage of the Commonwealth Government’s *Coastal Waters (State Title) Act*
4 *1980*, which had the effect of extending the law-making powers of the states (including Queensland)
5 to an offshore area up to 3 nautical miles from the shoreline. Reservations were made, however, within
6 the Act for the Commonwealth to retain control over the majority of the Marine Park (much of which
7 falls within 3 nm). Today, in addition to the federal Marine Park, there is also a state-based marine park
8 managed under the (now) *Marine Parks Act 2004* (Qld) covering an approximate coastal area of 63,000
9 square kilometres. The GBR Coastal Marine Park ‘is contiguous’ with the GBR Marine Park and includes
10 the area between low and high water marks and many waters within the limits of the State of
11 Queensland (Commonwealth and Queensland Government, 2015; Day, 2018; Day, 2019).

12 Since the mid-1990s, a flurry of state and federal laws, plans and policies were subsequently
13 introduced with an increasing emphasis on managing the quality of water entering the GBR Marine
14 Park. As Figure 1 below shows, four major bilateral water quality improvement plans were introduced
15 in the early 2000s (in 2003, 2009, 2013 and 2017). Paradoxically, whilst the Queensland and
16 Commonwealth governments have been willing to invest in water quality initiatives - currently
17 estimated to be \$614 million between 2017-2022 (Commonwealth and Queensland Government,
18 2018b, p. 9), both levels of government have been unwilling (or unable) to take a strong stance on
19 greenhouse gas emissions and fossil fuel exports from the domestic fossil fuel industry. The federal
20 government, in fact, has had trouble acknowledging the role played by CO₂ in anthropogenic global
21 heating, or the damage caused to the Great Barrier Reef by the amount of heating observed to date.
22 Court actions from non-government organisations have arguably had minimal impact on government
23 policy (Peel et al., 2017), and climate change remains the biggest threat to the health of the site (Great
24 Barrier Reef Marine Park Authority, 2019b).

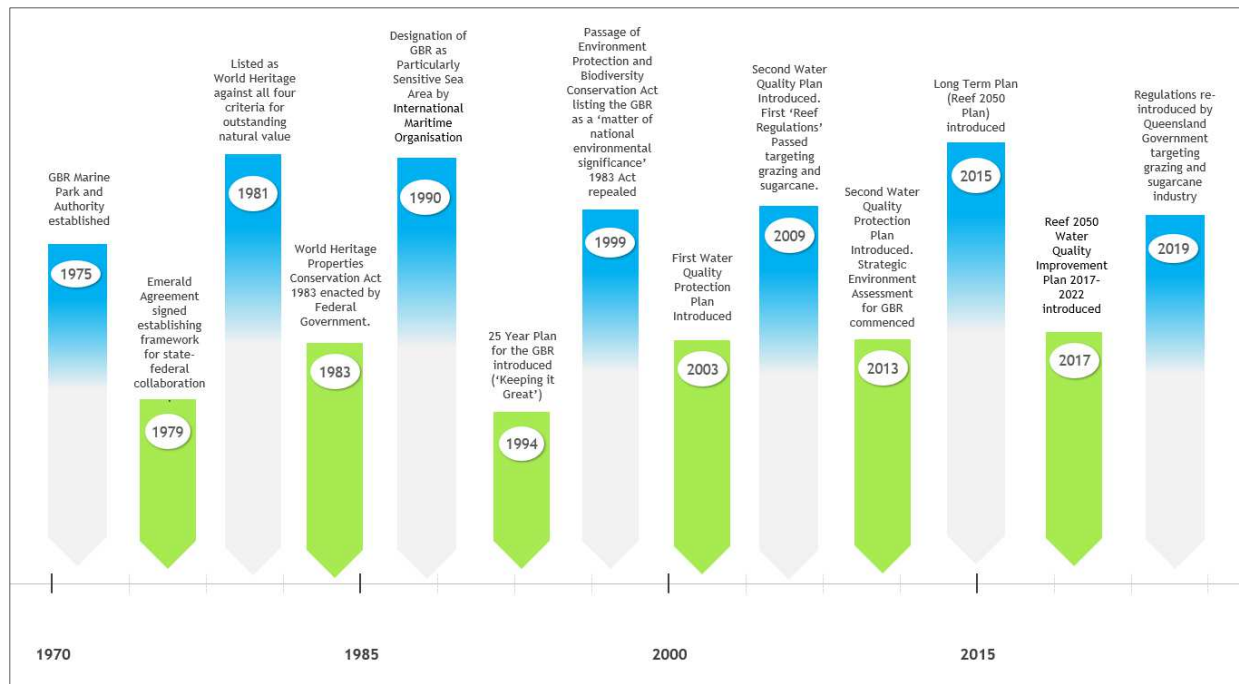


Figure 1: Key governmental interventions at the state and federal level for protection of the GBR 1970-2020

Nonetheless, the political turmoil of the last five decades has resulted in an increasingly intense policy focus on the regulation of direct actions affecting the GBR including: the banning of mining and oil development in the 1970s (Fraser, 1979); tightening requirements for shipping (Grech et al., 2013) and the prohibition of dredged spoil dumping within the Marine Park (Paredes et al., 2017). As the next section of the paper shows, regulation has also been utilised at the state level in an effort to restrict the clearing of native vegetation within the catchment as well as the excessive allocation of fertilisers to the soil.

3.2 Regulating Land Use in the Catchment

The catchment of the GBR is a vast geographic area subject to a wide variety of land uses from urban development and public infrastructure to port development and shipping, agriculture, tourism and resource extraction. There is no single planning instrument, nor decision-making authority, which covers both the Commonwealth Marine Park and catchment area in terms of permitted use. Moreover, whilst the local and federal governments do play some role in controlling land use across the catchment, by and large, the Queensland state government has the primary responsibility for regulating potentially environmentally-risky industries such as agriculture, mining and coastal development. As Table 1 (below) shows, the state government has enacted a wide range of regulatory frameworks that seek to control (and facilitate) land use across the catchment. It is important to note, however, that in the same way that federal-state laws conflict for the GBR, so too do administrative responsibilities across state agencies for implementing the regulatory frameworks in the GBR catchments.

Regulatory Framework	Legislative Instruments	Objectives	Key Components and Concepts
Planning	Planning Act 2016, Regional Planning Interests Act 2014, Coastal Protection and Management Act 1995.	Integrated system of land use planning and development assessment underpinned by principles of ecologically sustainable development (ESD).	Requirement for a development approval for assessable (and regional) development. Offences for non-compliant development, including clearing vegetation without a permit. Restrictions on removing sand and quarry material in the coastal zone.
Major Projects	State Development and Public Works Organisation Act 1972, Economic Development Act 2012.	Facilitation of major public and private infrastructure projects through the declaration of explicitly controlled areas. Driven by desire for economic progress.	Declaration by the state of Coordinated Projects and State Development Areas which fast track development. Declaration of Priority Development Areas (PDAs) within which community objection rights are limited and local planning instruments are overridden.
Mining	Mineral Resources Act 1989, Petroleum and Gas (Production and Safety) Act 2004.	To encourage the economic development of minerals and gas in the state, whilst minimising conflicts with other land uses.	Requirement for mining/petroleum lease and other licences for operating resource activities. Extraction and exploration also requires compliance with environmental protection and water use legislation.
Water Use	Water Act 2000.	Sustainable management of Queensland's water resources, including underground water reservoirs. Driven by the principles of ESD.	Requirement for water licence to extract underground water and riverine protection permits required for destruction of vegetation in a watercourse, lake or spring.
Pollution	Environmental Protection Act 1994.	Protection of the environment from air, water and soil pollution.	Requirement for Environmental Authority to undertake activities such as mining, aquaculture, intensive animal husbandry, chemical and petroleum production, and food processing.
Waste	Waste Reduction and Recycling Act 2011.	Waste avoidance and reduction, minimise the impact of waste on the natural environment	Provides for the introduction of a levy for certain waste as well as reporting and waste tracking requirements. Certain disposal practices are also banned.
Vegetation	Forestry Act 1957, Vegetation, Management Act 1999.	Management and ecologically sustainable use of the state's forested areas and regional ecosystems (woody vegetation).	Establishes a framework for regional ecosystems including 'relevant purposes' for which a landholder can clear their land. Works in tandem with the Planning Act 2016 to require assessment and approval.
Port Development	Sustainable Ports Development Act 2015, Transport Infrastructure Act 1994.	Management of port-related development in and around the GBR World Heritage Area.	Declaration of priority ports along GBR coast. Prohibition of capital dredging outside of priority ports. Requirement for Master Plan for each port. Restricted entry for port land.
Nature Conservation	Marine Parks Act 2004, Nature Conservation Act 1992.	Conservation and sustainable use of wildlife and protected areas in Queensland (national parks, reserves, marine parks etc.).	Offence to take or interfere with native wildlife (plants and animals). Restriction on activities within protected areas such as national parks, marine parks,
Cultural Heritage	Torres Strait Islander Cultural Heritage Act 2003, Aboriginal Cultural Heritage Act 2003, Native Title (Queensland) Act 1993.	Protection of cultural heritage places and artefacts throughout the state. Recognition of native title interests in land and waters.	Duty of care established not to harm Aboriginal or Torres Strait Islander cultural heritage. Requirement to negotiate with (and where required, compensate) native title holders.

1 *Table 1: Overview of the regulatory frameworks relating to land use in the GBR's catchment*

2

1 As Dale and others point out, Queensland's property and planning system is a 'highly
2 fragmented and [arguably] dysfunctional' regime (Dale et al., 2013, p. 9). There are many examples of
3 complicated and complex regulatory planning processes. The clearing of vegetation for pasture, for
4 example, is considered 'assessable development' and jointly regulated under the *Planning Act 2016*
5 (Qld), *Vegetation Management Act 1999* (Qld) and subordinate legislation. For legislative purposes,
6 such development is considered identical to undertaking urban development in the inner city, despite
7 the fact that the actions are vastly different in social and ecological impacts. Further, the extraction of
8 minerals may necessitate several licences under various Queensland legislation, including: the *Water*
9 *Act 2000* (Qld); *Environmental Protection Act 1994* (Qld); and *Mineral Resources Act 1989* (Qld). Certain
10 mining projects, in areas important for cropping may also require an additional authority under the
11 Queensland state government's *Regional Planning Interests Act 2014* (Qld). Within other areas of
12 concentrated development (for example, at the Abbott Point coal terminal on the GBR coast, or in the
13 Galilee Basin in central Queensland), a special 'State Development Scheme' may be in place which has
14 the effect, pursuant to Part 6 of the *State Development and Public Works Organisation Act 1971* (Qld)
15 of overriding local planning schemes entirely.

16 The end result is a complex, overlapping patchwork of regulatory coverage across the state that
17 (artificially) separates mining from other forms of development (both urban and commercial), waste
18 and recycling from industrial pollution, agricultural activities from food processing, and indigenous
19 artefacts and land use from non-indigenous heritage. The ability to undertake cumulative effects
20 assessment for a site like the GBR has been notoriously limited, although recent attempts have been
21 made to develop a cumulative impact management policy (Great Barrier Reef Marine Park Authority,
22 2018).

23 **4. The Regulation of Agricultural Land Use impacting Water Quality**

24

25 **4.1 Regulation of Agricultural Water Quality and Sugarcane Management Practices**

26 Agriculture currently accounts for 80% of total land use within the catchment of the GBR (Reef
27 2050 Water Quality Improvement Plan 2017-2020). In addition to beef grazing, discussed further below,
28 sugarcane cultivation has been a prominent industry in coastal areas of Queensland for over 150 years
29 (Moore, 1974). The sugarcane farming region, which stretches from Mossman in the north of the state
30 to the border with New South Wales in the south, produces 95% of Australia's sugar (Queensland
31 Economic Advocacy Solutions, 2019), most of it for export. There are five major sugarcane growing
32 regions in Queensland: (1) Far North Queensland; (2) Ingham, Burdekin and Ayr; (3) Mackay; (4)
33 Bundaberg-Wide Bay Burnett; and (5) South East Queensland (QEAS, 2019). The industry produces 4.5

1 million tonnes of raw sugar every year (Queensland Economic Advocacy Solutions, 2019), making
2 Australia the second largest exporter of sugar in the world (North Queensland Register, 2021). The
3 sugarcane industry has a long history of government regulation for economic purposes, particularly by
4 the Commonwealth for the twin goals of competitive international exports and a more equitable
5 distribution of the benefits between producers and exporters.

6 In terms of the environmental impacts from sugarcane cultivation, scientific consensus has
7 been steadily revealing a challenging picture for the industry (Waterhouse et al., 2017). Scientists and
8 policy makers have been aware of the impact of nutrient loads on water quality since the early 1970s
9 (e.g. Mitchell et al., 1997). Indeed, water quality impacts from land use in the catchment were
10 referenced in the original nomination for the GBR World Heritage site in 1981 (Great Barrier Reef
11 Marine Park Authority, 1981, p. 3). However, only recently have the Queensland and Commonwealth
12 Governments attempted to contain the water quality threats from sugarcane cultivation. The first
13 attempt occurred in 2003, with the introduction of the joint Queensland-Commonwealth Reef Water
14 Quality Protection Plan ('the 2003 Plan'). The 2003 Plan targeted 'diffuse pollution from broad scale
15 land use' (grazing and sugarcane) but did not extend to 'urban diffuse sources and point sources of
16 pollution such as sewage, waste from ore processing as part of mining and aquaculture'
17 (Commonwealth and Queensland Government, 2003 p. 2). A (rather fragmented) environmental
18 regulatory framework was already in place for controlling agricultural impacts on the environment (see
19 Table 1., above) and the 2003 Plan specifically noted that 'appropriate use of the wide range of existing
20 regulatory powers' was necessary to 'complement and support self-management and co-operative
21 partnership approaches' under the plan (Commonwealth and Queensland Government, 2003, p. 21).
22 However, it stopped short of introducing specific regulations targeting nutrient use in the agricultural
23 industry.

24 Although the overarching goal of the 2003 Plan was to 'halt and reverse the decline in water
25 quality entering the Reef within 10 years', by 2009, it was clear that the plan was ineffective at halting
26 declining water quality trends (Brodie et al., 2008) although significant additional funding was only
27 allotted in 2008 following the election of an Australian Labor Party government. A second Reef Water
28 Quality Protection Plan was devised in 2009 ('the 2009 Plan'). At the time, the scientific and policy
29 consensus was that: 'water discharged from rivers into the [GBR] continues to be of poor quality...[and
30 that]...the [2003-2009] management actions [were] not addressing the problem effectively.'
31 (Commonwealth and Queensland Government 2009, p. 3). The possibility of regulation thereafter
32 become a focus of the 2009 Plan, including, specifically, the desire to 'develop and implement new
33 [legislative rules]...for improving reef water quality' (Commonwealth and Queensland Government

1 2009, p. 21).

2 In 2009, after a period of consultation with industry, scientists and community groups, the
3 Queensland government passed chapter 4A of the *Environmental Protection Act 1994* (Qld) (2009
4 Regulations). The chapter 4A provisions (known colloquially as the ‘regulations’) had the intent of
5 criminalising farmer conduct, by way of a statutory offence, for ‘over-apply[ing] nitrogen or phosphorus
6 to soil, unless the farmer complied with an approved environmental management plan’ (Hamman and
7 Deane 2018, p 457). The 2009 Regulations were, however, never fully implemented, reportedly due to
8 industry backlash and a commitment from the Queensland government that water quality
9 improvements could be realised through voluntary Best Management Practices (BMPs) (Waschka and
10 Gardner, 2016 p. 207; Hamman and Deane 2018). This represented a shift from an enforceable co-
11 regulatory approach to a voluntary mode of self-regulation, as least as far as the regulation of nitrogen
12 use and water quality were concerned. As the Queensland Government recently reflected:

13 The Great Barrier Reef Protection Amendment Act 2009 introduced the first round of Reef
14 protection regulations. In 2012, a policy change associated with a change of government saw
15 the redirection of funding and effort to voluntary industry-led [BMP] programs and incentives
16 for the sugarcane and grazing sectors and the regulations were not enforced (Queensland
17 Government, 2018a, p. 2).

18 Between the years 2010 and 2015, the declining health of the GBR began to make world
19 headlines (Hughes et al., 2015). Whilst the initial attention started with the controversial approval by
20 the state government of a major gas development at Curtis Island and the huge dredging program
21 associated with the developments (e.g. Brodie, 2014; Paredes et al., 2017), it later morphed to include
22 all manner of developments along the GBR coast (McGrath, 2012). The focus also turned to cumulative
23 impacts on water quality, including sugarcane and grazing activities within the catchment areas
24 (Australian Government, 2014, p. 28). The international oversight of the World Heritage Committee,
25 principally driven by UNESCO and the International Union for the Conservation of Nature (IUCN),
26 eventually led to the development of a 2-year Strategic Environmental Assessment (SEA) for the GBR.
27 The SEA was undertaken pursuant to the federal government’s *Environment Protection Biodiversity and
28 Conservation Act 1999* (Cth). In short, UNESCO, IUCN and the World Heritage Committee had
29 threatened that, without improved conservation action at the site, including with regards to water
30 quality, the GBR was to be included on the List of World Heritage in Danger (World Heritage Committee,
31 2014).

32 The SEA provided a catalyst for a shift towards regulation, compliance and enforcement. By

1 2017, after parrying away threats of an ‘In Danger’ Listing, the Queensland government (in concert with
2 the Australian government) released a Consultation Regulatory Impact Statement (Queensland
3 Government, 2017) that proposed new regulations be utilised ‘as part of a mix of tools to accelerate
4 progress toward meeting the Queensland and Australian Governments’ Reef water quality targets
5 under the Reef 2050 Long-Term Sustainability Plan’ (Queensland Government, 2019a, p. 4). The
6 inclusion of the new regulatory package, alongside other policy interventions, had been recommended
7 by a 2016 taskforce report (Great Barrier Reef Water Science Taskforce, 2016). Also in 2016, the state
8 government had begun to focus more intently on the sugarcane industry including re-initiating some
9 basic ‘compliance activity’ of the existing regulations (Queensland Government, 2019b, p. 2). This
10 marked a shift in the regulatory strategy, but without a formal amendment to the law and minimal
11 amounts of consultation with industry.

12 Results of compliance activities published in 2019 demonstrate relatively high levels of non-
13 compliance (55% of initial inspections 2016-2019) which improved substantially on follow-up visits
14 (Queensland Government, 2020a). Technical non-compliance with the currently regulated practices in
15 sugar cane can occur due to a failure of soil testing or recordkeeping. Without records, this cannot be
16 distinguished from material noncompliance with nutrient application requirements. “Most growers are
17 non-compliant for a number of reasons” (Queensland Government, 2020a), so it is reasonable to
18 assume that most noncompliance growers are for both technical and material reasons. After follow-up
19 visits, non-compliance fell to approximately 30% and enrolment in voluntary practice change programs
20 increased (Queensland Government, 2020a). Results were, however, highly variable across catchment
21 areas, and high levels of compliance appeared to be associated with high levels of uptake of voluntary
22 industry BMPs (Queensland Government, 2020a). These results suggest that regulatory intervention,
23 coupled with increased compliance activity, complements voluntary approaches, such as BMPs, both
24 by encouraging participation in voluntary programs and prompting adoption in those that don’t
25 participate in voluntary programs.

26 The new regulatory package (which again took the form of Chapter 4A of the *Environmental*
27 *Protection Act 1994* (Qld)) was eventually passed by the Queensland Parliament in September 2019
28 (the 2019 Regulations). Prior to their passage, the Queensland Government (2019a, p. 4) summarised
29 the results of the regulatory impact consultation process as follows:

30 Feedback through various consultation processes ... consistently showed stakeholder views
31 were divided on further Reef protection regulation. Agricultural stakeholders prefer voluntary
32 approaches for meeting Reef water quality outcomes. The industrial sector (point source
33 nutrient and sediment contributors) believe they are already heavily regulated, and additional

1 requirements are disproportionate to the risk posed from the sector compared to the
2 agricultural sector. The conservation sector supports regulation as a necessary step to meet
3 the water quality targets. The Queensland Government believes the recommended Reef
4 regulatory package reflects feedback from stakeholders, while also achieving significant water
5 quality benefits.

6 The regulatory approach was amended to declare minimum practice standards for commercial
7 sugarcane, grazing and horticulture practices across all the catchment areas of the GBR. ERA minimum
8 standards will be ‘prescribed’ and standard conditions will likely relate to, amongst other things, the
9 use of water, nutrients, agricultural and chemical products on the farm, as well as the requirement to
10 conduct tests, including, for example, tests of soil, water and plants (*Environmental Protection Act 1994*
11 (Qld) s 81(3)) and to keep records. The regulations also allow for the Minister to set objectives for
12 reduced nutrient and sediment load, which are aligned with the Reef 2050 Water Quality Improvement
13 Plan 2017-2022. Operators will need to comply with the minimum standards prescribed, although some
14 operators will be able to meet the required standards through the successful completion of the
15 voluntary BMP program – or alternative ‘recognised accreditation program’ (*Environmental Protection*
16 *Act 1994* (Qld) s 82(3)).

17 In terms of their operation, the 2019 Regulations aim to ‘provide for measures to improve the
18 quality of the water entering the Great Barrier Reef’ (*Environmental Protection Act 1994* (Qld) s 74).
19 They provide for the establishment of a water quality policy in an effort to ‘reduce the load of each of
20 the contaminants entering the waters from each river basin in the catchment’ (*Environmental*
21 *Protection Act 1994* (Qld) s 77(2)). The term ‘load’ is defined as ‘the total volume of the contaminant
22 that enters the water in a year’ (*Environmental Protection Act 1994* (Qld) s 77(5)). The regulations
23 categorize certain activities within the catchment of the GBRWHA (i.e., commercial sugarcane, grazing
24 and horticulture activities) as ‘agricultural environmentally relevant activities’, or ‘agricultural ERAs.’
25 This categorization is consistent with how the *Environmental Protection Act 1994* (Qld) has defined
26 other potentially harmful activities in Queensland, such as coal mining, coal seam gas extraction,
27 aquaculture, feedlots, food processing and electricity generation

28 At the passage of the regulatory package, farming groups and conservative politicians
29 continued to resist the legislation arguing that it unfairly targeted parts of the industry that had made
30 significant gains in environmental stewardship (ABC News 2019a). The reality of progress under the
31 BMP approach adopted by the LNP government in 2012 (see above) has been revealed by the Australian
32 and Queensland governments’ 2019 Reef Report Card, with the two main agricultural industries on the
33 GBR catchment – sugarcane cultivation and rangeland beef grazing, performing poorly in reaching

1 targets for adoption of best management practices. Sugarcane cultivation scored E with only 9.8% of
2 land in priority areas managed to best management practice against a target of 90% by 2025. There
3 was minimal progress between 2016 and 2019. Beef grazing scored D with 35.8% of Great Barrier Reef
4 grazing area managed under best management practice systems against a target of 90% by 2025. There
5 was almost zero improvement between 2016 and 2019. The Queensland Government reiterated its
6 concerns that if the regulations were not adopted, then the World Heritage bodies may once again
7 consider the site for inclusion on the World Heritage In Danger List (ABC News, 2019b).

8 The 2019 regulations adopt a ‘staged’ approach and are to be rolled out progressively over a
9 period of three years across various parts of the catchment. The staged approach was considered
10 necessary in order to address ‘concerns from industry about the costs of the regulations, and the time
11 it will take producers to become compliant’ (Queensland Government, 2019a, p. 18). It was also
12 considered necessary to ‘better manage government compliance costs and capacity in response to
13 thousands of producers being regulated for the first time’ (Queensland Government, 2019a, p. 18).
14 Although there had been the threat of regulation in the past, the passage of the 2019 regulatory
15 package marked a formal shift from a self-regulation-style (at times enforced) towards more command
16 and control-style regulation.

17

18 **4.2 *Regulation of Land Clearing and Grazing Land Management***

19

20 Rangeland grazing, that takes place in the large and relatively arid catchments of the GBR – the
21 Burnett, Fitzroy, Burdekin and Normanby - is known to increase erosion rates greatly. This has caused
22 loads of fine sediment (and the associated particulate nutrients) discharged to the GBR to increase by
23 a factor of five following the agricultural development of the GBR catchment starting in about 1830
24 (Kroon et al., 2012). Erosion has increased through the formation of gullies, streambank erosion and
25 hillslope erosion (Bartley et al., 2018) and we know that specific areas within catchments have eroded
26 far more than others (Bartley et al., 2015). Grazing reduces pasture cover leading to the initiation of
27 gullies, increases hillslope erosion and the access of cattle to streams increases bank erosion.

28 According to the latest figures released by the Queensland government (Queensland
29 Government, 2018b) over 90% of clearing across the state is occurring for pasture. 91% and 93% of the
30 clearing mapped in 2016–17 and 2017–18, respectively, was assigned to the ‘replacement land cover
31 class pasture’ with the remainder utilised for ‘crops, forestry, mining, infrastructure and settlement’
32 (Queensland Government, 2018b, p. 1). Clearing of native vegetation (woody vegetation, not wetlands
33 or grasslands) in the catchment of the GBR was approximately 166 000 ha/year in 2016–17 and 148

1 000 ha/year in 2017–18 representing on average about 40% of total state wide clearing rates
2 (Queensland Government, 2018b, p. 2). The environmental impacts of recent clearing are exacerbated
3 by the historical actions that continue to impact on the region (Commonwealth of Australia, 2019).

4 Clearing native vegetation for pasture is considered ‘development’ in Queensland. Clearing is
5 regulated under the *Planning Act 2016* (Qld) and *Vegetation Management Act 1999* (Qld) as well as
6 subordinate legislation. There are certain ‘relevant purposes’ for which native vegetation can be
7 cleared. Whilst direct clearing for pasture (i.e. broad scale clearing) is not one of them, fodder
8 harvesting and clearing of encroachments and managing thickened vegetation may be permitted.
9 Clearing for fodder harvesting roughly makes up 50% of all applications (Department of Energy and the
10 Environment, 2017, p. 7). The Planning Act-Vegetation Management Act framework considers
11 proposals to clear as ‘application for development approval’ and accordingly, a failure to obtain a
12 permit, or comply with the relevant self-assessable code, may lead to compliance action. Recent data
13 from the Queensland government has shown that enforcement of tree clearing laws has dropped
14 significantly in recent years and rates of clearing are on the rise (Hamman, 2019).

15 In addition to the vegetation management act framework, the 2019 regulations which apply to
16 sugarcane operations, (discussed immediately above) also apply to ‘commercial’ cattle grazing in the
17 catchment (*Environmental Protection Act 1994* (Qld) s 79). As is the case with sugarcane, regulated
18 farmers in the catchment must not contravene an agricultural ERA standard. If the contravention is
19 wilful, the maximum fine is approximately AUD \$222,000, and if not wilful (for example, negligent or
20 careless), the maximum fine is approximately AUD \$80,000. The maximum penalty for a wilful offence
21 is in line with other serious offences under the *Environmental Protection Act 1994* (Qld) regime, for
22 example, unlawfully causing material environmental harm (*Environmental Protection Act 1994* (Qld) s
23 438(2)); and wilfully and unlawfully causing an environmental nuisance (s 440(1)) – offences which have
24 mostly been directed at waste and mining industries in Queensland.

25 Finally, in order to address legacy deterioration (Adame et al, 2019), the 2019 regulations,
26 when implemented through the ERA standard, will also likely require graziers in degraded landscapes
27 to ‘take steps to improve land condition and record the measures taken’ (Queensland Government,
28 2019a, p. 32). The regulator (Queensland Government, 2019a, p. 32) has foreshadowed that such steps
29 could include:

30 developing a property map, revising stocking rates, wet season spelling, managing preferential
31 grazing, excluding stock from high erosion areas, and monitoring and recording changes in land
32 condition. This improved flexibility should help reduce regulatory costs to graziers as they will

1 only be required to act if land condition is poor, and will be able to choose the most appropriate
2 path to an improved outcome for their property.

3 As with the cane industry, parts of the grazing industry strongly resisted the Queensland
4 Government’s regulatory approach. AgForce – the chief lobby group for Queensland graziers - strongly
5 opposed the 2019 regulations, arguing they represented ‘an unnecessary impost on farmers, [and] even
6 more red tape, that will provide absolutely no benefit to the reef in terms of water quality’ (Queensland
7 Country Life, 2019). In May 2019, AgForce deleted a decade worth of grazier’s self-assessment data
8 that had been collected through the delivery of a voluntary, government-funded best management
9 practice program (Smee 2019). The data deletion was in direct response to the proposal in the
10 regulation impact statement that the Minister would have the power to ‘require data from the
11 agricultural sector that may assist in determining where over application of fertiliser ... may be
12 occurring’ (Queensland Government, 2019a).

13 5. Discussion

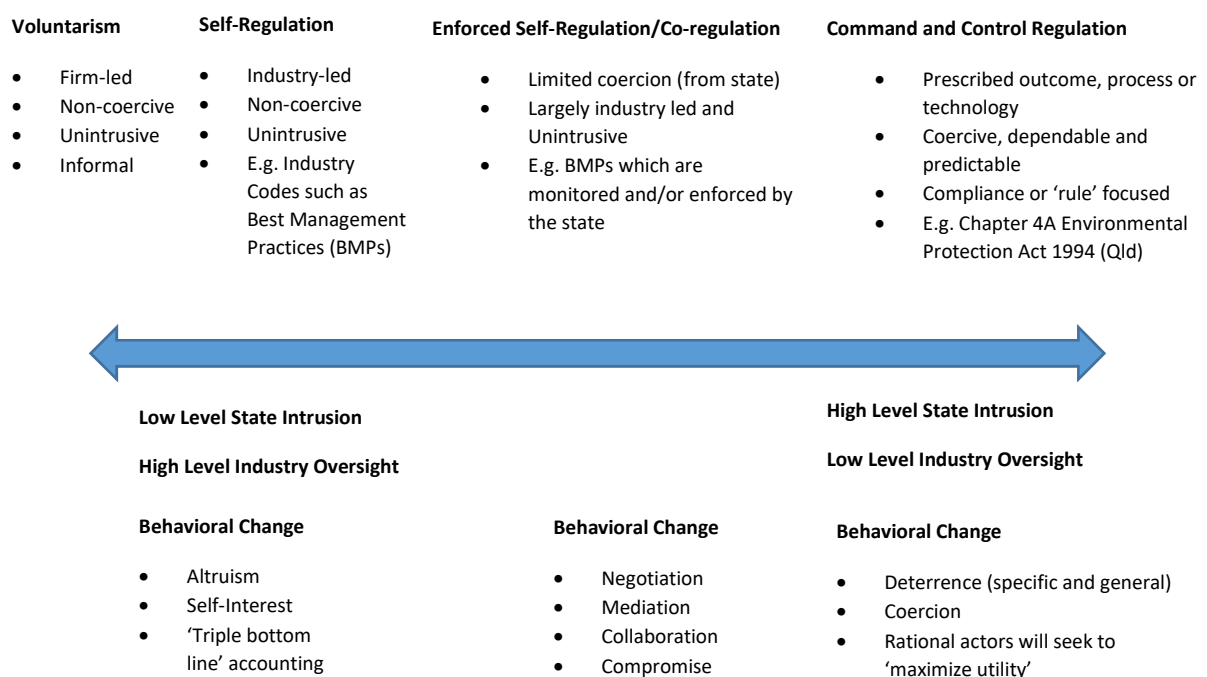
14

15 5.1 *Regulation as Part of the Policy Mix*

16 At its heart, regulation is the process of formulating rules and monitoring and enforcing those
17 rules (Hutter, 2006, p. 203; Levi-Faur, 2013). The term regulation can thus be functionally defined as
18 having three core elements: (1) a set of standards or rules with stipulated actions required; (2) a system
19 for monitoring of those rules; and (3) procedures for enforcement of the rules in instances of non-
20 compliance. The concept of regulation thus has a narrower frame of reference than ‘governance’ which
21 refers to a broader suite of policy instruments including legislation, regulation, markets, policies,
22 institutions, networks and behavioural norms (Chaffin et al., 2014).

23 There are various kinds of regulatory approaches or ‘theories’ about how regulation should
24 operate. Perhaps the most well-known is the command and control (CAC) model, whereby
25 governments establish rules and (often centrally) monitor and enforce compliance. Since the
26 deregulatory movement of the 1980s (Hutter, 2005), CAC models have fallen out of favour. Businesses
27 complained about stifling economic growth and ‘red-tape’. An alternative notion of ‘self-regulation’ has
28 thus emerged, described as ‘industry-level organisation (as opposed to the government or individual
29 firms) setting rules and standards (codes of practice) relating to the conduct of firms in the industry’
30 (Gunningham and Sinclair, 2017). As Sinclair (1997, p. 529) has summarised, ‘the search for regulatory
31 alternatives to [CAC] has led many commentators to promote, or at least contemplate, the use of self-
32 regulation to improve the environmental performance of industry.’

1 A considerable amount of sophisticated thinking on designing and implementing regulation,
 2 including environmental regulation, has taken place over the last three decades (Gunningham, 2011).
 3 Although ‘there is nothing remotely approaching consensus’ in terms of how regulatory measures
 4 should be designed (Gunningham 2011, p. 171), the bulk of the literature suggests that systems which
 5 are ‘smart’ (Gunningham et al., 1998) and ‘responsive’ (Ayres and Braithwaite, 1992) are likely to be
 6 more effective. Modern approaches to regulation encourage a broad suite of actors to be involved in
 7 regulatory tasks, including non-state actors such as non-government organisations (NGOs), scientists,
 8 research institutions and private corporations. Models of co-regulation and self-regulation are
 9 promoted as an alternative or complement to more traditional government-administered regulation
 10 (Eijlander, 2005). As Scott (2001) suggests, a deeper understanding of the complexities of the given
 11 ‘regulatory space’ is also required. Such an analysis can help to identify precisely who needs to be
 12 regulated (i.e. the ‘regulatee’), what needs to be regulated (i.e. the regulatee’s actions) and who should
 13 be doing the regulating (i.e. the regulators). Figure 2. below showcases the diverse suite of regulatory
 14 and co-regulatory approaches available to policy-makers in the GBR context. It shows the extent of
 15 state oversight with each option and the assumptions upon which behavioural change is thought to
 16 occur (self-interest, deterrence etc.).



17
 18 Figure 2: Typologies of Regulation including with reference to the Queensland Sugarcane Industry
 19 (Gunningham and Sinclair 1999; Eberhard et al. 2020)

20

1 As Figure 2 above demonstrates, the self-regulatory model has no government enforcement
2 whereas the co-regulatory approach largely includes industry codes (such as BMPs) that include rules
3 or standards subject to effective monitoring and enforcement by regulators. We might consider this
4 space to be the ‘regulatory environment’ (Fidelman et al., 2019) or ‘regulatory space’ (Scott, 2001) of
5 the larger governance system. As Fidelman and others (2019) have noted:

6
7 the regulations and the entities responsible for their development and implementation (e.g.,
8 government agencies) [together] comprise the regulatory environment (p. 222)

9
10 Though it is often considered a matter of last resort as a policy approach (Gunningham and
11 Sinclair 2005, p. 75), regulation (with state backed enforcement) is often necessary to complement
12 other policy levers (Gardner and Waschka, 2012). Although soft-law (or ‘carrot’ approaches) such as
13 voluntary schemes and financial incentives are often politically palatable for governments, the
14 ‘regulatory gorilla lurking in the closet’ (Verbruggen, 2013) has been shown on numerous occasions to
15 help drive behavioural change (Knook et al., 2019). Indeed, Kroon et al. (2014) found that programs
16 that had successfully reduced nutrient and sediment exports to receiving waters all included some non-
17 voluntary mechanisms, either driven by underpinning legislative and regulatory intervention (e.g.,
18 China, Denmark) or economic collapse (e.g., eastern Europe). Thus regulation, designed with care and
19 sophistication, can and should form part of a functioning environmental governance system. Although
20 in other jurisdictions, self-regulation has proved to be (largely) sufficient to bring about positive changes
21 (Yoder et al., 2020). For instance, the Everglades Forever Act in Florida mandated the adoption of best
22 management practices to reduce phosphorus loads but ‘devolved implementation to farms collectively
23 rather than requiring individual compliance’ (Yoder et al., 2020). However, in the case of regulating land
24 use in the GBR catchment, there has been a ten-year period of a (predominately) ‘self-regulatory’
25 approach which has not delivered the water quality results urgently needed (Commonwealth and
26 Queensland Government, 2019; Eberhard et al., 2017). At the reintroduction of the regulations, in
27 2019, the Queensland Government confirmed there were no other viable alternatives to
28 (re)introducing regulation as a response (Queensland Government, 2019b, p. 8):

29 Since 2009, the Queensland Government has invested over \$70 million in industry-led BMP
30 programs, science and on-ground programs to assist landholders in improving their agricultural
31 management practices. Additionally, significant funding has been available under a range of
32 Queensland and Australian government programs to assist producers to voluntarily improve

1 their practices. These opportunities have been embraced by many growers and landholders.
 2 However, there are still large numbers who choose not to make the necessary changes. In these
 3 circumstances, regulation is the only suitable tool to bring everyone up to minimum practice
 4 standards.

5 Accordingly, it is considered reasonable that some form of efficient regulatory intervention,
 6 which includes the threat of state backed enforcement, be a part of the policy mix of approaches.
 7 Indeed, numerous studies of the GBR catchment have made recommendations to that effect (see e.g.,
 8 Brodie and Pearson, 2016; Gardner and Waschka, 2012; Waschka and Gardner, 2016; Great Barrier
 9 Reef Water Science Taskforce, 2016; Waterhouse et al., 2017; Eberhard et al., 2017; Hamman and
 10 Deane, 2018). Allied to targeted regulatory intervention is the need for GBR basin-specific pollutant
 11 load reduction targets (Brodie et al., 2017) to be adopted and also supported by a detailed,
 12 comprehensive, costed water quality management plan for the GBR (Waterhouse et al., 2017; Great
 13 Barrier Reef Water Science Taskforce, 2016; Brodie and Pearson, 2016; Eberhard et al., 2017) and
 14 evaluated through adequate modelling data to ensure water quality targets are indeed achieved (Yoder
 15 et al., 2020). As with other policy interventions, regulation should be carefully designed in the most
 16 economically efficient manner where regulators can best use their limited resources. In the next section
 17 of the paper we discuss the need for risk-based regulatory approaches and canvass the approach
 18 currently adopted in Queensland.

19

20 **5.2 Understanding and Responding to Risk**

21

22 The 2019 regulations, discussed above, affect grazing, cane and other agricultural and industrial
 23 land uses in the catchment. It seems clear that the types of land uses captured by the intervention have
 24 expanded since the previous self-regulatory (sometimes with enforcement) approach of 2009. The
 25 2009 and 2019 regulations both utilised the EP Act as the legislative vehicle for implementation. There
 26 were some important differences, however, in terms of regulatory approach and coverage, as set out
 27 in Table 2: below.

Focus	2009 Regulatory Package	2019 Regulatory Package
Legislative approach	Requirement for Environmental Risk Management Plan for regulated operators. Offence not to comply.	Removes need for Environmental Risk Management Plan. Creates minimum practice standards and farm design. Allows regulated operators to meet compliance through voluntary BMPs.
Catchment coverage	Only three Regions: Wet Tropics, Burdekin and Mackay Whitsundays ('Priority Catchment Areas')	All GBR Reef catchment areas (Regions) including Fitzroy, Cape York and Burnett Mary.

Regulated industries	Commercial cattle grazing, banana and sugarcane cultivation.	Cattle grazing, banana and other horticulture, sugarcane and other grains, as well as point source pollutants from sewage, waste from mining, and aquaculture.
Regulated operators	3,300	13,000
Potential for Offsets	Not permitted	Where an activity cannot avoid or mitigate impacts on water quality, then a water quality offset may be provided for.

1

2 *Table 2: Comparison of scope and focus of regulatory interventions in 2009 and 2019*

3

4 The 2019 regulations were implemented on an understanding that they would assist, along
5 with other policy levers (voluntary BMPs, incentives, market-based mechanisms etc.), in eliminating
6 'high risk practices that contribute to excess nutrient and sediment run-off' (Queensland Government,
7 2019b). Moreover, both the 2009 and 2019 regulations targeted certain agricultural practices that were
8 believed to be 'higher risk' in terms of their potential impacts on the receiving environment (the waters
9 of the GBR). Underpinning such an approach, though perhaps not made explicit in all aspects of the
10 legislation, is the central idea of risk.

11 Risk-based regulation has been an increasingly accepted policy approach since the 1980s
12 (Hutter, 2005). In more recent times, substantial theoretical effort has been directed towards the
13 concept of risk-based regulation, especially in the United Kingdom (Baldwin and Black, 2008). At its
14 heart, risk-based approaches involve the design of interventions that seek to more effectively allocate
15 resources of the regulators to where the problems are most likely to occur. Or, as Gunningham (2011,
16 p. 174) puts it, it involves an 'evaluation of [the] degree of risk to the environment posed by the
17 infraction'. Risk-based approaches are thus concerned with prioritisation. That is, with allocating scarce
18 regulatory resources (finances, technical expertise, equipment, know-how etc.) to places where they
19 are most needed (Roach, 2015). Baldwin and Black (2008, p. 66) summarise the concept as follows:

20 [Risk-based approaches] provide a systematic framework that allows regulators to relate their
21 enforcement activities to the achievement of objectives. They enable resources to be targeted
22 in a manner that prioritises highest risks, and they provide a basis for evaluating new regulatory
23 challenges and new risks.

24 An alternative, though not dissimilar, conception is provided by Rothstein et al (2006):

25 [Risk-based regulation involves] allocating resources in proportion to risks to society (such as
26 health, safety or environmental risks), considering both the impacts themselves and the
27 likelihood that they happen, in order to establish appropriate levels of control.

28 And, more broadly in relation to risk-based approaches in governance, Hutter (2005) writes:

1 The risk approach centres on determining probability and impact factors, deciding on
2 regulatory response, the development of regulatory tools and most importantly, informing
3 allocative decisions in deploying limited resources.

4 Risk-based regulation is not without its challenges (Hutter, 2005; Rothstein et al., 2006)
5 including gathering the public's trust (Roach, 2015) but it has considerable relevance to the problem of
6 nutrient and sediment run-off impacting the GBR. The Queensland Government introduced the 2009
7 and 2019 regulations on the basis of scientific consensus about the land use practices that were
8 considered the highest risks – that is, that were most likely to be causing water quality impacts
9 (Queensland Government, 2019a, pp. 1-2). It seems clear that our understanding of water quality
10 impacts – in particular the relative impact of different land uses - has improved remarkably since the
11 first policy interventions were formulated in the early 2000s. For example, the state government is now
12 able to estimate, utilizing the best available science, that in the major land uses of sugarcane and
13 grazing, a majority of farmers are still using moderate and high risk practice categories. In sugarcane
14 cultivation, the government estimates that 4% of farmers are reportedly in the low risk category, 14%
15 in moderate risk, 70% in moderate-high risk and 12% in high risk for nutrient (fertilizer) practices
16 (Commonwealth and Queensland Government, 2019). Such an assessment, based on data from
17 voluntary programs, is vital to ensure regulators (and their rules) target scarce resources towards where
18 the environmentally-riskiest activity is likely to occur.

19 In terms of compliance, the regulator has foreshadowed an approach that will focus regulatory
20 effort on high-risk operators, noting that they will 'prioritize compliance' through technological tools
21 such as remote sensing, direct monitoring and desktop analysis (Queensland Government, 2019b, p.
22 9). Since 2015, compliance, was already being spatially targeted by catchment and sub-catchment area
23 and proximity to key waterways. The focus had been, for instance, on 'record keeping, soil testing and
24 fertilizer use' of farms primarily in the Burdekin and Wet Tropics catchment areas (Queensland
25 Government, 2020a). In terms of levels of compliance, recent data shows that 55% of cane growers
26 visited by compliance officers in high risk catchments in 2016-19 were non-compliant with the existing
27 2009 regulations (Queensland Government, 2020a).

28 While prioritisation on the basis of pollutant sources (catchments, industries and sub-
29 catchments) is obviously a sensible approach to risk-based regulation, tools like 'heat maps' produced
30 with technological aides (e.g., remote sensing) are likely to be 'insufficient for choosing which action to
31 take in a given location' (Tulloch et al. 2015). Threats to the receiving environment are not always
32 spatial, indeed they are also temporal and the behaviors of regulated entities are sociologically complex
33 and often poorly understood. In the case of the GBR catchment, *the behavior* of individual farmers

1 across the catchment is unpredictable and accordingly it may be that a spatial threat map approach, on
2 its own, may be of reduced value to regulators. What is likely required, therefore, is an approach that
3 encompasses a spatial and temporal understanding of the water quality impacts, coupled with a
4 deeper, more sophisticated behavioral understanding of the activities of regulated entities in key parts
5 of the catchment. Further, impacts of practice change on water quality have largely relied on modelling,
6 both in the GBR and in other parts of the world (Yoder et al., 2020). Therefore, in order to improve
7 farmer and industry responses there may be a need to better link water quality data with on farm
8 decisions (Yoder et al., 2020). Linking compliance to water quality is also critical for understanding the
9 effectiveness of the regulations in overcoming material non-compliance.

10
11 It is important to note, however, that the existence of uncertainty and unpredictable context-
12 dependence does not mean that risk-based decisions are not effective, or superior to other
13 alternatives. It is reasonably well understood that a wide range of factors influence landholder decisions
14 about the adoption of new practices, based upon their learning and experience, personal characteristics
15 and circumstances and the characteristics of the practice itself (Pannell, 2006). Adoption decisions are
16 thus “highly contextual, contingent and specific” (Taylor and Eberhard, 2020). Studies in the GBR have
17 demonstrated that different farmer cohorts have distinct values and motivations that will influence
18 their responses to communications and engagement (Rolfe and Gregg, 2015; Emtage et al., 2007;
19 Greiner and Gregg, 2011; Emtage and Herbohn, 2012). As well as individual adoption decisions,
20 participation in programs is influenced by trust and engagement pathways, transactions costs,
21 perceptions of risk and cultural dimensions (Taylor and Eberhard, 2020). Peak agricultural bodies, for
22 example, can play critical leadership roles in facilitating landholder engagement in voluntary or
23 regulatory programs, while at the same time advocating for agricultural policy changes, including
24 resistance to environmental regulations. It is to the attitudinal and institutional environment of the
25 agricultural industry in Queensland we now briefly turn.

26 27 **5.3 Attitudinal Settings and the Broader Institutional Environment**

28
29 Baldwin and Black (2008) suggest five key aspects of a regulatory regime that ought to be
30 considered when devising and implementing regulatory systems of control. Two of the more important
31 considerations, at least for the purposes of this paper, are (1) understanding the attitudinal settings
32 and (2) the broader institutional environment in which the industry exists. Both of these factors should
33 ideally be carefully considered for regulation to work in the instances in which it is applied.

34 As Haines (2017) writes:

1 Too much regulation raises concern. Disparate actors voice their opposition to ‘red tape’,
2 ‘green tape’ and the overweening influence of ‘the nanny state’... This debate that oscillates
3 between too much and too little regulation provides a critical insight into the way that
4 regulatory reform and the challenges of compliance are part of an ongoing political discourse.

5

6 In many ways, the attitudinal settings of the cane and grazing industries largely reflect genuine
7 resistance to regulatory oversight (Hamman and Deane, 2018). As demonstrated through public
8 discourse surrounding the *Vegetation Management Act 1999* (Qld) (Simmons et al 2018) and the 2009
9 and 2019 Regulations over the last decade (Hamman and Deane 2018; Deane et al 2018), these
10 industries have had strong reactions to regulations, including lobbying in response to the 2009
11 regulations by the sugar industry to bring about the BMP compromise (Hamman and Deane 2018;
12 Deane et al 2018). In response, governments at both the state and federal level have tended to resist
13 the use of CAC-style regulation, especially in areas considered to be ‘less than straight forward’ in terms
14 of demonstrating immoral or criminal conduct. Concomitant to this, is the observation that
15 governments have generally moved away from direct CAC regulation since the 1980’s (Gunningham,
16 2009), while Craig and Roberts (2015) note the lack of political will to regulate diffuse water quality and
17 the resistance from agricultural industries.

18 The sugarcane industry is no stranger to regulatory oversight, which may at least in part explain
19 the industry’s opposition to it. The economic operation of the industry (trade, logistics, supply chains
20 etc.) has been regulated since the early 1900s. The 2009 and 2019 Reef Regulations were resisted by
21 industry and perceived as an unnecessary and unwelcome intrusion into their private land use affairs.
22 Presently in Australia there are estimated to be 4,400 sugarcane growers (Rural and Regional Affairs
23 and Transport References Committee, 2015). The majority of these are sole proprietors or family
24 partnerships, however the dependence on Mills means that growers often have to be within a close
25 area proximity (Rural and Regional Affairs and Transport References Committee, 2015). Although there
26 are 21 sugar mills, most of which are owned by overseas entities (Courier Mail, 2019) there are also
27 many other stakeholders associated with the ongoing operations of this industry. The number of
28 entities in the sugar supply chain means that transaction costs imposed by regulatory interventions may
29 be distributed across a range of operations. Indeed, the financial viability of the sugarcane industry in
30 Queensland hinges on the cooperative action of the growers combined with the work of the mills
31 (Hildebrand, 2002). Just as the growers are dependent on the mills, the mills are also dependent on
32 volume of production, and therefore crop yields (Deane et al., 2018). Mills have relatively high
33 operating costs that includes a combination of a large equipment base and a number of salaried

1 employees (Hildebrand, 2002). Because the costs of operating a sugar mill are significant, the income
2 associated with a particular throughput are necessary, without which a mill would cease to be an
3 ongoing financial concern, which is problematic for those who have a proprietary ownership structure.
4 This means that the regulation of grower behaviour, where it may impact on yield or industry
5 participation may be resisted by the industry collectively. The convergence of financial interests may
6 therefore result in strong opposition to any regulatory oversight.

7 In the context of cattle grazing, the situation is likely to be different again. The reportedly
8 isolated nature of large properties may mean that the social influences may be less significant than for
9 cane growers. Like sugarcane, however, many grazing enterprises operate on small profit margins and
10 are highly susceptible to drought and other climate-related impacts to their operations. Moreover,
11 while there is evidence that there are net economic benefits of maintaining soil and pasture resources
12 in good condition and reducing stocking rates in drought conditions (O'Reagain et al., 2011), there are
13 significant lag periods in landscape recovery (10–15 years) that mean financial benefits are often
14 deferred (Wilkinson et al., 2013b; Bartley et al., 2014) and responses highly variable by land type (Star
15 et al., 2013). Further, this may also mean that the costs are imposed upon those who have not caused
16 the environmental damage, at least not in its entirety (Sharpley et al, 2013). These factors may prevent
17 the adoption of more sustainable land management practices (Ash et al., 2015; Rolfe et al., 2016a) and,
18 perhaps explains the strong resistance by landholder groups towards the reintroduction of regulations
19 and subsequent deletion of BMP data. In any event, there is likely to be a large variability in the cost-
20 effectiveness of management actions in grazing lands across different land types and land conditions
21 (Star et al., 2013; Rolfe et al. 2016a). Moreover, gully and riparian erosion is likely to reflect historical
22 as well as contemporary management practices, and remediation of large gullies will continue to be
23 high cost, high risk, with little private benefit (Brooks et al., 2016).

24 Also in this context, it is important to recognise the entrenched property rights (both freehold
25 and leasehold) that graziers lay claim to may politically (although perhaps not legally) restrain the
26 actions of government. As McGrath (2018, pp. 26-27) points out:

27 The decision to lease land, sell land as freehold, dedicate it as national park or other tenure
28 [has] an immense effect on the use of the land. This creates the fabric of tenures [in
29 Queensland], which then in practice heavily constrain the environmental legal system due to
30 the property rights associated with each tenure and a reluctance to interfere with those rights
31 without paying compensation.

32 All of this creates significant resistance in the grazing and cane industries to any form of direct
33 regulatory oversight, further highlighting the need for governments to use regulation as part of policy

1 mix of instruments seeking to change behaviour. Indeed it is difficult to generalise about the regulation
2 of agricultural land use across the entire GBR catchment, and, as a recent report noted, 'efficient policy
3 solution sets are actually regionally specific ...[meaning that]... Reef-wide and inflexible policies may
4 inadvertently increase the cost of meeting [regulatory] targets (Alluvium 2016, p. iv).

5

6 ***5.4 The State-Federal Regulatory Nexus***

7

8 One element that has not been addressed by either the 2009 or 2019 regulations (nor perhaps
9 could it have been) is the institutional and regulatory overlap which exists between the state and federal
10 governments with respect to water quality entering the site. Whilst the federal government has
11 financially supported water quality measures in the catchment, it has resisted implementing a
12 complementary regulatory approach to land use, despite the legislative mandate to do so. The role of
13 the federal government in environmental regulation of the catchment, should, however, not be
14 discounted, even with the passage of 2019 regulations by the Queensland government. However, it is
15 essential that the roles of state and federal governments compliment, rather than conflict, with one
16 another (Hamman et al 2021).

17 As Eberhard and others (2017, p. 465) have argued, there is a 'need to effectively manage [the]
18 ongoing cycles of change and disruption [regarding the GBR], and [pay] close attention to power and
19 politics'. The hierarchical functions of government in Australia, entrenched as they have been to our
20 federalist model of democracy, make effective networked governance approaches out of reach most
21 of the time (Eberhard et al., 2017). This is not particularly surprising for the case of the GBR, though it
22 is exemplified in many respects given the scale of the site and the enormity of the political and socio-
23 ecological challenges the GBR faces. As Eberhard and others (2017, p. 465) conclude:

24 efforts to employ networked governance approaches to address water policy conflicts [have]
25 struggle[d] to effectively bridge the hierarchical functions and authority of governments with
26 the potential for productive and creative networked relationships.

27 Indeed, the effective governance of enormous socio-ecological systems (SES) like the GBR, can be
28 undermined by uncoordinated or disjointed jurisdictional and institutional relationships across the
29 biogeographical system. As Evans and others (2014, p. 399) note, the governance challenges arise as a
30 result of:

1 connectivity and boundary issues between the land-sea interface, external drivers impacting
2 the marine [site], and the current lack of effective polycentric institutions to govern the region
3 at the scale of the larger coastal [site].

4 Recent work has therefore suggested a collaborative approach to the management of land use
5 within the catchment of the GBR (Kroon et al., 2014). However, collaboration must also be carefully
6 choreographed. For instance, in response to an adaptive management approach and with a view to
7 supporting local knowledge (see Commonwealth of Australia, 2019), delegating authority to the level
8 of government closest to the problem would likely be beneficial, but at the same time it is essential to
9 nesting innovation in a higher level of government. This model has been referred to as ‘supportive
10 subsidiarity’ (Deem, 2021) and could enable the benefits of cooperative federalism to be realised
11 without causing unnecessary red tape. Although consideration could be given to the additional use of
12 the *Great Barrier Reef Marine Park Act 1975* (Cth) and the *Environment Protection and Biodiversity and*
13 *Conservation Act 1999* (Cth) to help regulate catchment activities (Brodie and Pearson, 2016; Eberhard
14 et al., 2017b) the bulk of the regulatory activities can and must remain the responsibility of the state of
15 Queensland. As noted, this is particularly important to reduce the risk of overlap, as there has been
16 some tendency in Australia for Commonwealth involvement in policy and service delivery to result in
17 repeated failures to achieve desired outcomes (Deem, 2021). Hitherto, the Federal government has
18 avoided duplicating Queensland’s regulation of land use practices in the catchment, but at the same
19 time, the objective of improving water quality is unlikely to be met without improved policy
20 collaboration to support the benefits of diversity and experimentation that federalism can provide
21 (Deem, 2021). A complementary role could mean that the Federal Government, with the benefit of
22 their extensive resources, could administer and resource complementary voluntary initiatives, including
23 research and innovation, which is essential to the ongoing health of the GBR. Currently the
24 Commonwealth does play this role, for example, through the \$700 million already provided to
25 Australia’s ‘Reef Trust’.

27 ***5.5 Evaluating the Impact of Regulation***

29 The Queensland and Australian Governments have committed significant funding to the issue
30 of water quality improvement including evaluating the effectiveness of programs and governance
31 mechanisms (Queensland Government 2019c). There is funding set aside for transparency and
32 accountability as well, including over \$2million AUD to make data and information publicly available
33 (Queensland Government 2019c). As Yoder (2020) and others have noted, this will be essential to

1 ensure the desired water are achieved in the long-term due to the uncertainty that surrounds the
2 extent that BMPs can deliver these outcomes.

3 Recent research has argued for an increase in funding to support catchment and coastal
4 management delivery systems to the required levels identified to address the pollution issues for the
5 GBR by 2025, that is, meet the water quality targets (Great Barrier Reef Water Science Taskforce, 2016;
6 Tarte et al., 2017). This is likely to require expenditure of 1 billion dollars annually over the next 5–7
7 years in contrast to the current expenditure of about one-tenth of this (Brodie and Pearson, 2016;
8 Alluvium, 2016). Exploring alternative financing, including the establishment of structured ecosystem
9 service markets, funding from private sources, and enhanced market delivery models may mean there
10 will be more funds available to devote to this.

11 Some of these funds must be devoted to better data and water quality monitoring. Time lags
12 between on farm management changes and positive environmental outcomes means that long-term
13 monitoring is essential, particularly if continual improvements in decision making is desired. Arguably,
14 the lag period may be caused in part by soil nutrient legacy caused by past management practices
15 (Garnache et al, 2016; Sharpley et al, 2013). Yoder et al note that ‘while studies generally show that
16 BMPs are effective in reducing phosphorus, the legacy effects of nutrients mean it can take anywhere
17 from 4 to 20 years to reliably detect improvement in water quality at meso-scale (1.100 km²)
18 watersheds’. Rigorous and effective evaluation is therefore essential to a successful long-term
19 approach.

20 In support of this, as Morrison points out, there likely needs to be a far ‘better understanding
21 of interactions, resources and opportunities at multiple scales is crucial to the effectiveness of regional
22 management’ (Morrison, 2007, p. 238)). We suggest that in introducing new restrictions on farmer
23 behaviour, the government must be prepared to invest appropriately in reviewing and evaluating the
24 changes both of the level of compliance and of the water quality. There is currently a five-year period
25 for reviewing the objectives set in policy (section 72) but this could be expanded to review the
26 government’s efforts in implementing the policy as well (not just the objectives themselves). If this was
27 intended, then it should be made clearer in the Bill. Further thought should also be given to whether
28 this should be a three-year period given the urgency of the issues facing the GBR. The review of the
29 regulations could coincide with a statutory evaluation of the compliance program, preferably
30 undertaken by a third-party independent provider, such as the Queensland Auditor-General, to ensure
31 full transparency and accountability in regulatory oversight (see e.g. Queensland Audit Office, 2017).

32 Importantly, regulation is just one of a number of policy instruments employed simultaneously in
33 the GBR. Farmers are a diverse group that will respond differently to different instruments. Moreover,

1 the understanding of what changes behaviour in the catchment’s agricultural community (and sub-
2 communities) is still underdeveloped, especially from a social-science perspective (Eberhard et al,
3 2021). Regulation will likely influence uptake in voluntary programs, and vice versa (as evidenced by
4 the results of the current compliance program described earlier) although, the challenges lie not only
5 in changing future behaviour, but also in reversing the ‘legacy deterioration caused by intense and
6 diverse land uses in the catchments’ (Adame et al, 2019).

7 Accordingly, the evaluation of 2019 regulations should incorporate not just their design and
8 implementation, but also their impact on different cohorts of farmers (regions, industries, enterprise
9 characteristics, motivations and values) and the interaction of compliance activities and other policy
10 instruments, including industry best management practice programs, extension and grants programs.
11 The greatest impact of regulations is likely to be found in optimising the mix of policy instruments and
12 their implementation across catchments, rather than seeking a ‘silver bullet’ to achieve environmental
13 standards.

14 **5. Conclusion**

15

16 It is clear that the ecological health of the GBR is at a cross-roads. Regular assessments of marine
17 water quality in the lagoon based on an extensive monitoring and research program have shown that
18 water quality is generally in a poor, and worsening, condition. Whilst some progress has been made in
19 reducing loads of fine sediment and nutrients in river discharge (and pesticide concentrations) there
20 are no significant signs of improvement in the water quality status of the marine waters of the GBR
21 (Brodie et al., 2019), although the benefits from previous actions have been projected. The outlook for
22 the world heritage values of the Marine Park is very poor (Great Barrier Reef Marine Park Authority,
23 2019b) and the urgency for strong and effective management clear to all. Current approaches to water
24 quality management are insufficient to achieve water quality targets (Waterhouse et al., 2017).

25 Many studies examining management of water quality for the GBR in the face of climate change
26 have compiled lists of well thought-out recommendations which the authors concluding would
27 expedite successful management (e.g. Waterhouse et al., 2017; Eberhard et al., 2017; Great Barrier
28 Reef Water Science Taskforce, 2016; and Brodie and Pearson 2016). In this paper, we have examined
29 the role of regulation within the broader GBR governance architecture. The arguments in this paper
30 could be strengthened with a broader comparative analysis across other jurisdictions. However, we
31 have not attempted to do this here and it remains a task for future research. A preliminary conclusion
32 we draw in this paper is that international empirical evidence supports the assertion that regulatory
33 interventions, coupled with strong compliance programs could reasonably be expected to be part of

1 the mix of policy instruments used by governments to facilitate the adoption of appropriate land
2 management practices.

3 The Queensland Government has taken tentative steps to regulating agricultural runoff in GBR
4 catchments, first in 2009 and then more recently in 2019. The (re)introduction of regulations has been
5 highly contested and compliance has been limited and enforcement inconsistent over time. However,
6 the reinvigorated compliance program seems to show some promising results as noted in section 4 of
7 this paper, especially when coupled with the use of voluntary programs. Despite the long history of
8 substantial investment in voluntary programs, awareness of regulatory obligations still appears to be
9 low, but farmers have seemed to be responsive to the staged introduction of compliance activities. The
10 2019 regulations, despite their unpopularity with agricultural advocacy groups, appear to provide a
11 rather sophisticated and scientific approach to managing the issue of agricultural run-off that should
12 complement other voluntary programs and market-based measures (such as water quality offsets)
13 financed through the Reef Trust.

14 We conclude that some form of [CAC]-style regulation and compliance is an important and
15 necessary part of the GBR policy mix required to meet urgent water quality targets. A self-regulatory
16 approach (and even co-regulation) has arguably proved insufficient over time. We commend the spatial
17 prioritisation of regulation and compliance effort employed by the Queensland Government that is
18 consistent with the principles of responsive and risk-based regulation. However, the impact of
19 regulations on diverse farmer cohorts, and the interactions between regulation and compliance
20 activities and other policy instruments needs to be carefully evaluated to allow the full benefits of
21 regulation to be realised.

22 Finally, although we recommend that the detail of direct regulation is a matter for state
23 governments, it is essential that the state and federal governments work together to support the
24 improvements in environmental outcomes of the GBR. A supportive approach is needed by the federal
25 government to aid in data collection, financial support and scientific assessment to ensure actions taken
26 are effective in achieving desired water quality and land restoration outcomes. Through a collaborative
27 approach the political risks of industry resistance and its potential to distort communication and
28 engagement with the farming community could be addressed through meaningful consultation.
29 Critically, there needs to be a stronger emissions reduction policy from the federal government (and
30 indeed the rest of the world) to ensure that any benefits of water quality improvement for the GBR are
31 not overwhelmed by climate change impacts.

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33

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