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Future of the Sea: Ocean Acidification

Foresight – Future of the Sea
Evidence Review

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Future of the Sea: Ocean Acidification

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Executive Summary

Ocean acidification (OA) and climate change are both influenced by increasing carbon dioxide concentrations coming from the atmosphere. However, the distinction between OA and climate change, is that OA is an alteration of the chemistry of seawater, therefore not a direct climatic process. The ocean is the largest natural reservoir of dissolved carbon and holds an immense buffering capacity for changes in atmospheric CO_2 concentrations. The rapid increase of atmospheric CO_2 since the industrial revolution has caused oceans and seas to absorb increasingly greater amounts of CO_2. This process disturbs the pre-existing chemical equilibrium of the sea, resulting in seas changing their chemical state and altering the ocean pH.

Ocean acidification has become one of the most studied topics in the last 10 years (Williamson et al. 2017; Browman 2016). The UK has made a significant contribution in understanding OA effects on biodiversity and biogeochemistry, and the socio-ecological impacts across species and ecosystems. The evidence suggests that OA will act differently across species with some impacts already occurring for sensitive marine species and with direct and indirect repercussions for ecosystems. The direct effects will include changes in species morphology, ecology and behaviour whilst indirect effects may be repercussions for processes or higher trophic groups (e.g. wider food web effects and interactions within and between species). This review summarises the available ‘state of the art’ information with regards to OA effects, current issues and further recommendations for consideration on what will be the likely future issues for OA. This information intends to support marine planning decisions and future policy adaptations. A detailed section is included on how these changes will affect UK interests (e.g. maritime industries, fishing, health and wellbeing). A summary of key highlights is outlined below.

- Monitoring data conducted over the North Sea assessments have shown clear pH changes in shelf and coastal sites. Trends of pH variability are still uncertain, and further work to disentangle the observed variability does require additonal investigation.

- By 2100, under medium emissions scenarios, ocean pH is projected to decrease by 0.3 pH units from levels 100 years ago. Evidence suggests that similar trends in acidification during the Paleocene-Eocene Thermal Maximum (PETM) (around 56 million years ago), where the rate of release of CO_2 was estimated to have been around one-tenth of current rate of anthropogenic emissions, caused the extinction of many seafloor organisms.
- Though the future impacts of OA on commercial fisheries are still uncertain, recent research has indicated that annual economic losses in the UK resulting from the effects of OA could reach US $97.1 million (GBP £7.47 million) by 2100.
- The integrity of some UK species and habitats of conservation importance (included under the current Marine Protected Areas – MPAs – designation) could be affected by future changes in pH and temperature.
- Ocean acidification research has demonstrated that some species may be more susceptible to changes in pH. These results are particularly important for UK shellfisheries and shellfish aquaculture, as these industries could be negatively affected.

1. Evidence for the Change and Drivers of Ocean Acidification

Increasing atmospheric CO_2 is causing an increase in seawater hydrogen ions (H^+) concentrations, reducing pH. These changes are quantified under a logarithmic scale, with seawater pH values decreasing as H^+ increases (see equations in Figure 1). Overall, when atmospheric CO_2 dissolves in sea water (H_2O), it forms a series of acid-base equilibriums effectively forming carbonic acid (HCO_3). Carbonic acid reacts with carbonate ions ($CO3^{2-}$) to form the stable bicarbonate ion (HCO_3^-). The overall consequence of these reactions is the acidification of ocean water. To date, observations have demonstrated that the mean global surface ocean pH has already decreased from around 8.2 to below 8.1, representing an increase of more than 25% in H+ concentrations.

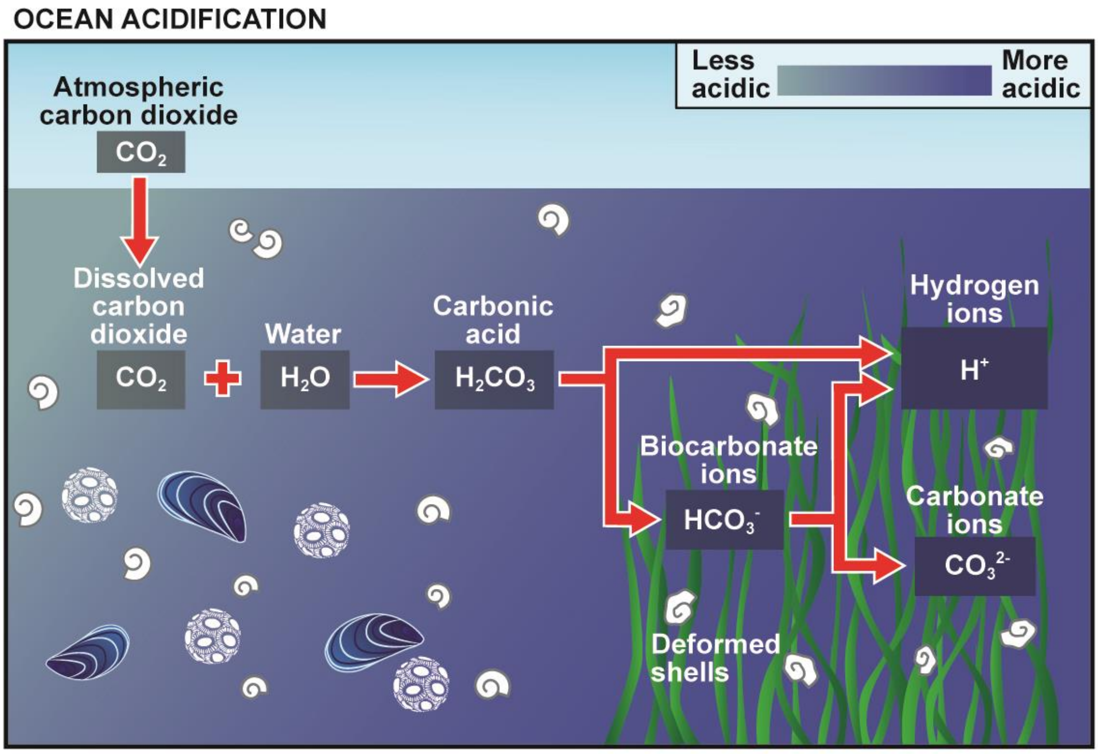

Figure 1. Schematic diagram of ocean acidification

The reaction between dissolved carbon dioxide (CO_2) and water results in an increase in the concentration of hydrogen ions (H^+); additional changes include an increase in bicarbonate ions (HCO_3^-), and a great decrease in carbonate ions (CO_3^{2-}); carbonate ions (CO_3^{2-}) will modify the carbonate saturation state; these changes lead to acidification.
Image: UK Ocean Acidification research programme, adapted from University of Maryland

These reactions can also reduce carbonate ions, in turn reducing the saturation state of seawater (denoted as Ω=omega). The saturation state of seawater for a mineral is a measure of the potential for the mineral to form or to dissolve. If Ω= less than 1, then carbonate ions are likely to dissolve with implications for marine calcifiers (such as molluscs, crustaceans and reef-forming corals), making it difficult for organisms to build and maintain their skeletons and shells. Modelling approaches suggest that from the 1850s to the 2100s, increased carbon dioxide dissolved in the water has led to lower aragonite saturation levels in the oceans around the world.

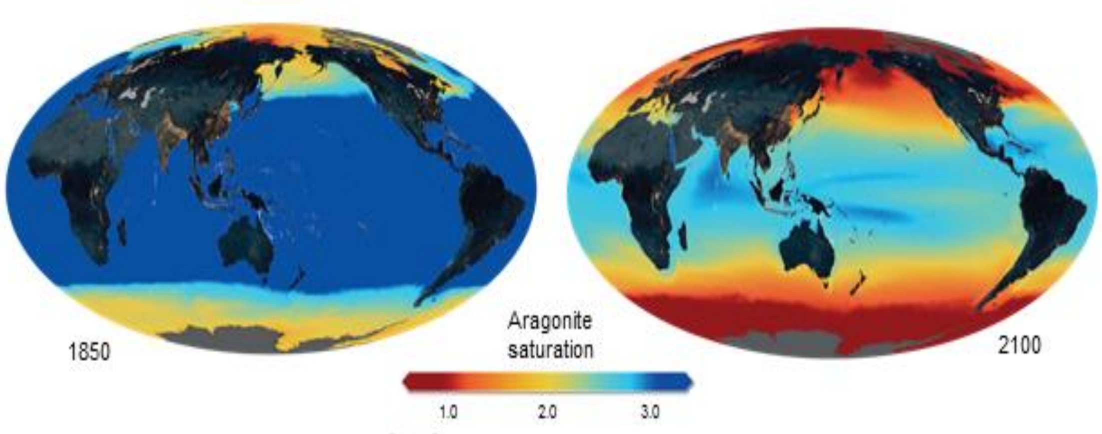

Figure 2. Ocean acidification changes mapped as aragonite saturation state indicating solubility of calcium carbonate in sea water

These changes are projected for 2100 compared to 1850, under high CO_2 emissions scenario (RCP 8.5)

Source: IGCBP, IOC, SCOR (2013)

Research has demonstrated that, using proxy evidence from isotopic analyses, previous atmospheric CO_2 was considerably higher than it is observed now and the available future projections are showing similar data patterns. Evidence suggests that values up to 1000 ppm have been calculated for the Paleocene-Eocene Thermal Maximum (PETM), about 56 million years ago, resulting from an intense volcanic activity. The rate of release of CO_2 was estimated to have been around a tenth of current rate of anthropogenic emissions, allowing more time for slow oceanic buffering processes to lessen the chemical effects as well as the effects for species, population and ecosystem adaptation on the overall biological impacts. The resulting global warming and changes in seawater chemistry caused the extinction of many seafloor organisms (Hönisch et al. 2012). The naturally driven OA during the PETM has been calculated as a decrease of 0.3 pH units in the surface ocean (Penman et al. 2014). Under medium emission scenarios, the projected pH decrease expected by 2100 is in line with this value. This includes the estimated decrease of around 0.1 pH units that has already occurred in the past 100 years (Williamson and Widdicombe 2017).

1.1 Ocean Acidification is Variable

The UK has been actively monitoring changes in carbonate chemistry around the UK, in the North-East Atlantic and Arctic, and in the Southern Ocean. A synthesis composed by a combination of repeated observations from: (i) fixed-point observatories (e.g. 'time series', at L4 off Plymouth, Stonehaven near Aberdeen), (ii) four Cefas SmartBouy sites, (iii) surveys conducted across gridded stations using the UK fisheries research vessels *RV Cefas Endeavour* and *RV Scotia*, and (iv) ad hoc research cruises on Natural Environment Research Council vessels have helped to compile existing baseline information. Together these datasets showed a strong temporal and spatial variability in pH and other components of the carbonate chemistry system vary. Overall data sets from the coastal time series show declining pH values over the sampling period of 2008–2015, whilst also revealing a strong seasonality pattern (Figure 3). At both L4 and Stonehaven, highest pH values occurred during spring and early summer (April–May/June) with lower values in autumn and early winter; there is also more rapid temporal variability (Figure 3).

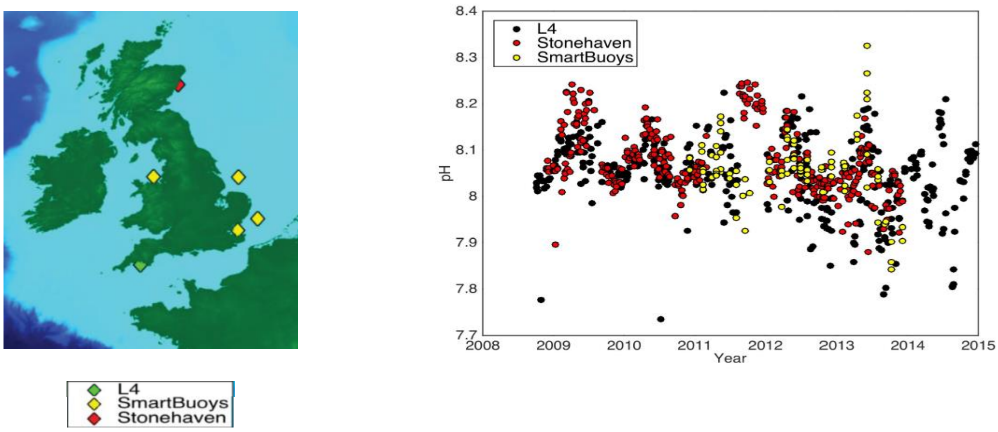

Figure 3. Overview of pH measurements

Calculated from DIC and TA) from the L4 and Stonehaven time series over 2008–2015 and SmartBuoys data from three locations (two from North Sea areas and one in the Irish Sea)

Source Ostle et al. (2016)

These intra-annual changes may in part be due to hydrodynamic effects (e.g. mixing/stratification, local currents and freshwater inflows) but mostly seem driven by two biological processes: photosynthesis (primarily by phytoplankton) that removes CO_2 from the water column, and respiration (by zooplankton, bacteria and benthic invertebrates), which completes the cycle by returning it. The general pH trends observed are similar at both sites. However, aragonite saturation values (affecting the solubility of calcium carbonate with repercussions for species needing to form structures) at L4 and Stonehaven show different ranges (2.1–2.5 and 1.8–2.2 respectively); these differences are primarily temperature-driven (Ostle et al. 2016). The observed variability of pH is greatest in coastal waters, which is of importance to commercial shellfisheries and aquaculture. The long-term decline in pH, due to increasing atmospheric CO_2, will need to be continuously monitored to understand how these coastal pH changes may be influenced by other stressors and potential repercussions for commercial species (e.g. mussels, cockles and oyster beds). The national observation programmes have helped to set UK baselines and have been adopted by the Department for Environment, Food & Rural Affairs (Defra) to support the compilation of national progress templates to report on the current state and support assessments under the EU Marine Strategy Framework Directive for achieving ‘Good Environmental Status’ (GES).

1.2 Future Projections

Ocean acidification effects for species, habitats and ecosystems, and their consequences for human society are extremely complex. However, we do now have improved understanding of these issues. The study of OA impacts and consequences requires transdisciplinary work (Yates et al. 2015), bringing together chemical, physiological, ecological and socio-economic research to properly assess whole-system effects and potential management responses. Blackford and Gilbert (2007) provided model outputs of OA in the North Sea assuming a range of CO_2 emission scenarios, and hence atmospheric CO_2 levels for the time horizons 2050 and 2100. Assuming atmospheric CO_2 increases to 500 ppm by 2050 (the median IPCC scenario), a decrease of ~ 0.1 pH units over most of the North Sea area is projected; however, if atmospheric CO_2 rises to 1000 ppm (worst-case IPCC scenario) over the next 50 years, a decrease of 0.5 pH units below pre-industrial levels is projected.

Recent UK modelling work for OA has concentrated on the development of shelf-sea simulations of carbonate chemistry. This work concentrates on seafloor processes, tidal currents, terrestrial inputs and overall ecosystem level processes over a high spatial resolution (~12 km). The model outputs showed a strong seasonality in sea surface pH, in the water column and at the seafloor. The model also evidenced a spatial and temporal heterogeneity, influenced by the hydrodynamics and biological activity (Artioli et al. 2014).

Most of the model work conducted to date has used future projections based on high-emission scenarios (e.g. A1B and RCP 8.5): under these conditions, the seasonal under-saturation levels of aragonite are projected for ~30 per cent of the bottom waters of the North Sea by 2100, with some surface under-saturation also included for some coastal waters in winter (Artioli et al. 2014).The conditions of saturated and under-saturated waters will have effects to the carbonate mineral (e.g. calcite, aragonite and high-magnesium calcites) from which marine organisms construct their shells and skeletons. If seawater becomes under-saturated, then these minerals will begin to dissolve, affecting marine species depending on these compounds to form their structures.

2. Ocean Acidification and the Effects on UK Interests

Ocean acidification research, based on experimental studies and meta-analyses over the past few years have revealed that certain taxa are very sensitive to changes in pH (Birchenough et al. 2015; Kroeker et al. 2013; Wittman and Pörtner 2013), whilst other taxa seem unlikely to experience any effects. Different responses to OA effects will vary across UK species and ecosystems. Evidence has indicated that crustaceans were less sensitive to these changes when compared to other groups (Wittman and Pörtner 2013). Larval fishes may be more sensitive to PCO_2 changes than some invertebrates, but still more research is needed to understand these responses (Wittman and Pörtner 2013). A recent study has also assessed the combined effects of OA and warming, demonstrating some effects for marine flora. Some species such as seagrasses and epiphytes may proliferate under lower pH conditions. However, these new conditions will not be optimum for calcified algae, causing some changes in their distribution (Brodie et al. 2014). These expected changes could have repercussions for ecosystem structure and functions as well as proliferation of invasive species, taking advantage of niches liberated by native fauna (Brodie et al. 2014).

Evidence also suggests that OA effects may exacerbate the overall effects of ‘nuisance’ species, producing further degradation of ecosystems services (Hall-Spencer et al. 2015). As the carbonate chemistry of the oceans is clearly changing, these new environmental conditions may favour the introduction of new species. For example, harmful bloom forming algae and invasive seaweeds, may benefit from these conditions (e.g. increased temperatures and decreasing pH), thriving in these modified environments. On the other hand, these new conditions may affect native fauna, causing mortality of displacement and creating modified habitats. These expected changes may have overall effects for ecosystems processes. However, the effects remain uncertain.

This information is particularly of relevance for commercially important species, species with conservation value and overall biodiversity. The sections below outline the available evidence and the likely effects on these key topics.

2.1 Impacts on Commercially Important Marine Species

Ongoing research under the UK Ocean Acidification (UKOA) and the Defra-funded PLACID (Placing Ocean Acidification in a Wider Fisheries Context) programmes conducted laboratory experiments on the effects of OA (and its interactions with temperature) on a wide range of marine species, including those of direct commercial importance. Results from these experiments have complemented the research carried out by the wider international scientific community. Results have demonstrated that certain groups of species (e.g. molluscs, echinoderms and corals) are generally more sensitive than others (e.g. crustaceans and finfish). However different life-stages (larvae, juveniles, adults, etc.) may exhibit different vulnerability levels for some species. Several studies have documented different responses to OA effects (Kroeker et al. 2013; Wittman and Pörtner 2013).

The future expected impacts of OA on shellfish fisheries (and indirect impacts on finfish fisheries) are still highly uncertain. Evidence gained from laboratory experiments has not been consistent enough to make detailed predictions. For some species, the increased level of food availability under the experimental conditions have minimised OA effects (Sanders et al. 2013). The effect of projected temperature increases (particularly under 'business as usual' scenarios) have been of much greater impact than OA on commercially important species of shellfish. Ongoing efforts attempting to 'scale up' from experimental results to consequences for fisheries in Europe and in the United Kingdom have confirmed that OA could have significant negative consequences in the longer term (e.g. Narita and Rehdanz 2016; Pinnegar et al. 2012; Le Quesne and Pinnegar 2012). However, there are still many uncertainties surrounding these effects.

A recent study on the potential impacts of OA and warming on future fisheries catches, revenue and employment in the UK fishing industry under different CO_2 emission scenarios showed that species were likely to be more affected by OA and warming combined, than by ocean warming alone (Fernándes et al. 2016). This work found that projected standing stock biomasses could decrease by 10–60 per cent; losses in revenue could decrease by 1–21 per cent; and losses in relevant employment (fisheries and associated industries) could be 3–20 per cent during 2020–2050 (Fernándes et al. 2016). In Europe, a wider analysis (Narita and Rehdanz 2016) suggested that annual economic losses resulting from OA effects by 2100 could amount to US $97.1 million, $1 million and $12.7 million (GBP £74.7 million, £0.77 million and £9.8 million) in the UK, the Channel Islands and the Isle of Man respectively under a worst-case scenario, mostly due to impacts on scallop fisheries. Within the UK, Wales and Northern Ireland seemed the most susceptible to damage to mussel culture (mainly in relation to production), whereas South West England is most susceptible in terms of the potential for lost oyster production.

2.2 Implications for Species of Conservation Importance

The cold-water coral *Lophelia pertusa* forms biodiverse and functionally important deep-water reef habitats in the North Atlantic, including Scottish waters and the Celtic Sea (Guinotte et al. 2006). In the UK, experimental studies have indicated that these species may be particularly vulnerable to OA. For example, by 2060, around 85 per cent of known deep-sea cold-water coral reefs in the UK could be exposed to waters that are corrosive to them (Jackson et al. 2014). Seven Marine Protected Areas (MPAs) have been designated for the protection of cold-water corals to date (Jackson et al. 2014). Similarly, for the horse mussel beds (*Modiolus modiolus*), which are designated features in 10 Marine Protected Areas, studies based on future climate change projections demonstrate a potential risk that this feature will no longer be represented in the UK marine protected area network by 2100 due to rising sea temperatures and OA (Gormley et al. 2013). The potential importance of OA for Marine Protected Areas within British Overseas Territories (BOTs), covering both tropical and polar conditions, may also have to be considered as these areas could be under threat. The risk to warm water coral reefs, and interactions with bleaching, are clear causes for concern, yet more evidence is required to fully understand these likely future effects. There may be a need to have operational OA monitoring in the BOTs, particularly those with associated Marine Protected Areas, e.g. the British Indian Ocean Territory (BIOT) and the Pitcairn Islands. However, significant costs would be involved.

3. Policy Implications for Ocean Acidification

The study and monitoring of OA effects in species and the marine environment is not a statutory obligation, however, it is closely linked to national (UK Climate Change Act 2008; Marine and Coastal Access Act 2009), European and regional (EU Marine Strategy Framework Directive, Convention for the Protection of the Marine Environment of the North-East Atlantic – OSPAR) reporting, and UN-related

(Sustainable Development Goal (SDG) 14;[1] governance decisions of the Convention on Biological Diversity) policy drivers. In the USA from 2007 to 2008 the oyster hatchery in Washington State lost up to 75 per cent of its larvae. At the time, industry had limited knowledge on how OA contributed to these losses (Barton et al. 2012). Nowadays, there is an active monitoring programme of pH and water conditions supported by an active network of industry, scientists and policy-makers, helping to minimise future losses and monitoring the early larvae developments. The USA's active model of science-industry-lawmaker collaboration has helped the industry adapt and respond to rapid changes in ocean chemistry. The effects of OA have not been felt in a similar way in the UK as those experienced by the US oysters farms. Nevertheless, the need to continue supporting monitoring practices could help to prevent these types of mortalities to safeguard these stocks in the British Isles where discrete oyster beds are distributed (e.g. West Mersey Estuary, Essex and Ireland). A recent review conducted on oyster biology highlighted the key role of these reef-forming species in the provision of wider ecosystem services such as improving water quality, coastline protection and food provision. This synthesis showed how these species could be likely affected by OA (Lemasson et al. 2017).

3.1 Future Research Needs

The emerging field of OA science has increased our awareness and understanding of the problem enormously, learning from ongoing practices (Riebesell and Gattuso 2015). Evidence suggests the following ongoing research needs.

1. Understanding the context for the variability observed in acidification observed in UK coastal waters, for example understanding the effect of sea-level rise. Continuous monitoring in UK coastal and shelf-sea sites would help to deliver this.

2. Improved understanding on the ability of all species, including shellfish and fish, to tolerate and/or adapt to acidification. This may require new studies (from

[1] SDG Target 14.3: "To minimise and address the impacts of ocean acidification including through enhanced scientific cooperation at all levels".

laboratory to in situ) to take account of the local environmental conditions and the species' natural environment prior to setting experimental tests.

3. Integrating current knowledge on the sensitivity of marine species (e.g. shellfish and aquaculture resources) to future OA would help to support industry and users to ensure readiness for climate change and OA effects.

5. Fostering knowledge transfer and collaboration on current OA practices (e.g. experimental evidence), local variability assessments with international partners could help to standardise current and future practices, as well promoting integration of new scientific knowledge.

6. Understanding species' evolutionary adaptation to OA, several techniques are available (e.g. molecular techniques) and some preliminary work is available.

7. Understanding potential 'bioindicator' candidates to monitor OA changes and effects, particularly on early larval stages, has the potential to act as 'sentinel' species and support future monitoring work.

8. Understanding natural gradients of carbonate chemistry as potential analogues of OA will help test different species' and ecosystems' responses over a wider spectrum of change, and can help to understand tipping points to develop understanding on ecosystem functions.

3.2 Other Response Priorities

Ocean acidification research and advice is constantly evolving. Research has shown that further understanding on how species adapt to OA and to other stressors is needed. This could provide valuable advice to support the potentially affected sectors and end users (e.g. aquaculture, fisheries, tourism, recreational activities). In the future, sea-food sectors in particular may have to consider more-adaptive management strategies to ensure stocks are safeguarded in support of food security.

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