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Impacts of land use on water quality and the viability of bivalve shellfish mariculture in the UK: A case study and review for SW England

James L. Webber[a,*], Charles R. Tyler[a], Donna Carless[a], Ben Jackson[a], Diana Tingley[a], Phoebe Stewart-Sinclair[b], Yuri Artioli[c], Ricardo Torres[c], Giovanni Galli[c], Peter I. Miller[c], Peter Land[c], Sara Zonneveld[a], Melanie C. Austen[d], A. Ross Brown[a]

[a] College of Life and Environmental Sciences, University of Exeter, Geoffrey Pope Building, Stocker Road, Exeter, Devon EX4 4QD, UK
[b] School of Biological Sciences, The University of Queensland, Goddard Building, Brisbane 4072, Queensland, Australia
[c] Plymouth Marine Laboratory, Prospect Place, The Hoe, Plymouth PL1 3DH, UK
[d] School of Biological and Marine Sciences, University of Plymouth, Drake Circus, Plymouth, Devon PL4 8AA, UK

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ABSTRACT

This paper examines how land use affects water quality and how this impacts the viability of shellfish mariculture (marine aquaculture) in the UK through a synthesis of the current literature, stakeholder workshops and targeted engagement of cross-sector organisations across a case study in South West England. We examine the importance of water quality as a constraint for shellfish mariculture in South West England and explore how current and projected future land uses are likely to influence ongoing viability. Currently, faecal material from agricultural runoff and municipal wastewater discharges is the main water quality issue affecting the viability of shellfish mariculture. Most UK Shellfish Waters, including those in SW England (~90%), do not consistently meet regulatory standards for faecal indicator organisms (FIOs) in shellfish, designed to ensure they are safe for direct human consumption. Other pollutants currently impacting shellfish mariculture include persistent organic pollutants and metals, suspended solids and excess nutrient inputs. Emerging pollutants with the potential to impact on mariculture include a range of consumer- industrial- and agri- chemicals, including biocides, pesticides, veterinary and human medicines. We evaluated possible changes in water quality conditions through deriving and exploring a range of future scenarios, considering policies and trends in land use including regenerative and intensive agriculture, renewable energy generation, afforestation, urban development and climate change. Our findings highlight possible trade-offs and synergies between land and water-based food production systems, applicable in SW England and across other regions of the UK and internationally, for helping to inform environmental policy development and implementation.

1. Introduction

1.1. Current food production systems are unsustainable

Current food production systems are far from sustainable (Rockström et al., 2009; Steffen et al., 2015). The majority of food is produced using land-based agriculture, which has a current footprint spanning over a third (5 billion hectares) of the Earth's surface (Ramankutty et al., 2018); the majority of which is used for rearing grazing livestock (Herrero et al., 2015; Froehlich et al., 2018). This pressure is set to increase, with future food production needing to sustain a growing human population, estimated to reach ~9.8 billion by 2050 (United Nations DESA, 2015; Tilman et al., 2017). Consequently, the agricultural land requirement for food production will likely to exceed the available land space by 2050 (Garnett et al., 2015; Röös et al., 2017).

Continuing to feed a growing population using land-based agriculture, whilst managing the compounding challenges of climate change (Piacentini et al., 2018) and competition for space from other land uses such as housing and renewable energy (Poggi et al., 2018), has led to an intensification of practices. This has resulted in degradation of soil health and fertility (Norris and Congreves, 2018) and disruption to agriculture-dependent ecosystem services, including, but not limited to, nutrient cycling, pest regulation, greenhouse gas regulation and carbon sequestration (Beddington, 2009; Godfray et al., 2010). Delivering

* Corresponding author.
E-mail address: J.Webber2@exeter.ac.uk (J.L. Webber).

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future food security therefore requires a fundamental change in the way that food is produced (Beddington, 2009; Smith, 2013).

1.2. Aquaculture as part of the solution for food security

Aquaculture, the farming of finfish, shellfish and seaweeds has huge potential in helping to meet future demands for sustainable food production (Bostock et al., no date; Godfray et al., 2010; Herrero et al., 2015) and globally is the fastest growing animal food production sector (Ottinger et al., 2016). Recently aquaculture has overtaken capture fisheries, now producing 82 million tonnes of food fish (worth US$232 billion per year), with projections rising to 109 million tonnes by 2030 (FAO, 2020).

The majority (63%) of global aquaculture production currently takes place in freshwater systems (Weitzman, 2019). Since only 0.01% of inland waters are habitable for fish (Stiassny et al., 1996), there is intense pressure in these areas and problems are further compounded by uncertainty in the future availability of freshwater due to climate change (Lynch et al., 2016). Furthermore, land-based expansion of aquaculture at the size and scale needed to satisfy future demands will inevitably result in conflict with other land uses and with the urgent need for the preservation of freshwater biodiversity, which has been more negatively impacted than in any other environmental compartment (WWF, 2018; Sánchez-Bayo and Wyckhuys, 2019).

1.3. The potential of marine aquaculture (mariculture)

There is considerable potential to develop marine and brackish aquaculture production in almost every coastal country, therefore a significant contribution to future aquaculture growth is likely to come from the expansion of marine aquaculture ('mariculture') (Kapetsky et al., 2013; Froehlich et al., 2018; Costello et al., 2020). It has been estimated that current total landings of all wild-capture fisheries could be produced by farming less than 0.015% of the world's ocean area (Gentry et al., 2017). Mariculture offers a number of advantages over land-based food systems in the relative efficiency of production in three-dimensional space, thus generating much smaller spatial and environmental footprints. One study estimates that diverting future growth in food production towards mariculture could save around 750 million hectares of land, an area twice the size of India (Froehlich et al., 2018). This shift would also result in significantly lower carbon emissions (Röös et al., 2017). Projections, taking into account a range of ongoing policy reforms and technological innovations, indicate that seafood production (principally from mariculture) could feasibly increase by 36–74% (i.e. by 21–44 million tonnes) by 2050. This could supply 12–25% of the estimated increase in meat protein needed to feed the estimated 9.8 billion world population in 2050 (Costello et al., 2020). However, a key constraint on the future expansion and success of mariculture (particularly shellfish mariculture) is impaired water quality, which can significantly limit food production and food safety. This pollution often originates from land-based sources (Brown et al., 2020b).

1.4. Bivalve shellfish, a sustainable food source susceptible to pollution

More than half of global food fish production from mariculture (currently 28.7 million tonnes per year) (FAO, 2020) comes from bivalve shellfish, which can be grouped into four major groups: clams, oysters, mussels and cockles. A total 79 marine bivalve species are cultured (versus a total of 93 wild caught species) according to the FAO Global Fishery and Aquaculture Statistics database (Smaal et al., 2018). These shellfish provide healthy sources of energy and protein, and are rich in vitamins (A and D), essential minerals (iodine, selenium calcium) and omega-3 fatty acids (Schug et al., 2009; EFSA, 2014).

Bivalve shellfish are also among the most sustainable mariculture products, since they derive their food entirely from naturally occurring food sources, based on marine planktonic microalgae. The growth of these algae is fuelled by natural (and anthropogenic) nutrient supplies from land runoff and coastal upwelling (Huston and Wolverton, 2009). Bivalve shellfish aquaculture also has the potential to deliver a number of ecosystem services, notably relating to enhancing water quality (Ferreira and Bricker, 2016; Froehlich et al., 2017). This is of particular relevance in terms of removing excess nutrients from water, and can be cost effective at a catchment scale (Lindahl et al., 2005; Nielsen et al., 2016; Petersen et al., 2016). For example, mitigation of eutrophication in EU coastal waters via nitrate removal by shellfish mariculture has been valued at US$20–30 billion per year (Ferreira et al., 2009; Smaal et al., 2018). Other prominent ecosystem services include habitat provisioning, fisheries enhancement and coastal protection (Weitzman, 2019).

1.5. Realising the potential of bivalve mariculture requires better management of land use

The food provisioning and multiple additional ecosystem service benefits of bivalve mariculture are not yet widely appreciated or exploited (Lindahl et al., 2005; Higgins et al., 2011; Ferreira and Bricker, 2016; Nielsen et al., 2016). This is particularly apparent in the UK, where bivalve mariculture production is considerably lower than in neighbouring European countries (Ferreira and Bricker, 2016; European Environment Agency, 2018). Static or declining bivalve shellfish production in the UK has been attributed to lack of strategic direction, competition for space in heavily utilised coastal areas, highly precautionary approach to licencing, and variable water quality that fuels concerns over shellfish quality, driving negative public perception and limiting domestic consumer demand (Huntington and Cappell, 2020).

The reliance of shellfish production on good water quality requires effective catchment management of land based activities (Lee and Morgan, 2003; Bricker et al., 2014; Environment Agency, 2019a). Impairment of water quality in estuarine and coastal Shellfish Waters is due principally to microbial agents (including human pathogens) and chemical contaminants introduced largely from land-based sources (Lee and Morgan, 2003; Lindahl et al., 2005; Pelletier and Tyedmers, 2010; Maxwell et al., 2016; Ottinger et al., 2016; Gentry et al., 2017; Gephart et al., 2017). Land use management and the control of land-based pollution is therefore a key challenge facing the development of bivalve mariculture, especially since these filter feeding shellfish are highly efficient in accumulating contaminants, which may render them unsafe to eat. (Froehlich et al., 2018; Brown et al., 2020b).

In this paper we review the interactions between land-use, water quality and the development of bivalve mariculture, with a focus on South West England, through analysing literature and synthesising findings from expert stakeholder engagement. Our paper is structured through first highlighting the contaminants presenting the greatest risk to bivalve shellfish and their consumers, key sources leading to their release and the strength of the evidence is regarding their impacts. Our second section examines land use practices currently driving pollution in South West England and explores preventative management options from whole catchment approaches to targeted mitigation measures. Our final section derives and explores how a set of scenarios evaluating the evidence and trajectories of likely future changes in land and environmental management pertinent to water quality and the long-term viability of bivalve mariculture in the UK.

2. Methods

An initial stakeholder workshop was undertaken to establish key constraints and knowledge gaps for managing water quality for the future sustainability and prosperity of mariculture in SW England (for further details see Brown et al., 2020b). The findings from the workshop were used to direct a critical review of published literature (reported here) to identify links between land use and water quality and mariculture viability. In a second (virtual) workshop, 104 regional and national stakeholders, representing: farming (6), water/waste (15), environmental regulation (15), conservation (33), and academic research (35) were engaged in the evaluation of current and likely future pressures on water quality and mariculture viability and to explore and develop realistic best-case and worst-case scenarios to facilitate the modelling and future management of SW catchments. Virtual workshop participants listened and responded to a series of 5-minute introductory presentations given by an invited panel that outlined a range of agricultural land use and management schemes designed to maximise profitability and sustainability of farming, whilst reducing the impact of agriculture on soil and water quality through different mechanisms. The presentations covered: a) agro-ecological/regenerative farming practices (Food Farming and Countryside Commission, 2019); b) nutrient management and emissions trading (National Farmers Union, 2020); c) natural flood management (South West Water, 2020); d) participatory catchment-based approaches (CaBA, 2020); e.) farmer advice on catchment sensitive farming practises (Environment Agency, 2019b).

Workshop participants were then randomly assigned to one of six separate breakout groups and provided with a common set of three short questions regarding possible future changes in agricultural land use and management over the next 10–30 years (Table 1). Participants were encouraged to consider future scenarios based on environmental drivers (e.g. climate change, flood risk, habitat change, pollution) and socio-economic drivers (e.g. policy, demographics, economic, technological), all of which influence the way we use land and water.

2. Results and discussion

2.1. *What are the key contaminants, sources and evidence regarding land use impacts on the viability of bivalve mariculture?*

2.1.1. *Microbial contaminants*

Microbial contaminants (including the pathogens norovirus, enterococci and salmonella) present primary risks to bivalve mariculture (Bussi et al., 2017). The consumption of contaminated shellfish has been linked to outbreaks of infectious intestinal disease and significant impacts on the National Health Service, as well as on the shellfish industry, through loss of sales, product recalls and loss of consumer confidence (Campos and Lees, 2014; Hassard et al., 2017). Microbial contaminants enter water courses via municipal sewage (human faeces) and agricultural sources (livestock faeces), particularly during high rainfall and run-off events. Flood events may also cause resuspension of microbial agents (Gooday et al., 2014), such as the FIO, *Escherichia coli* (*E. coli*), which can persist in freshwater sediments for periods of several weeks (Davies et al., 1995; Perkins et al., 2016). *E. coli* counts in saltwater water and shellfish can often exceed statutory limits for direct human consumption (300 counts per 100 mL of water; 230 counts per 100 g of shellfish flesh), which in turn can lead to protracted downgrading (below Class A) of UK (and EU) Shellfish Waters under EU Food Hygiene Regulation (EC) No. 854/2004 (European Council, 2004a). This currently prevents the export of live bivalve shellfish harvested from the majority (~90%) of UK shellfish waters (Food Standards Agency, 2021).

Table 1
Breakout discussion questions exploring likely future scenarios for land management and water quality in SW England.

(a) How effective are environmental stewardship schemes likely to be in terms of improving and maintaining water quality?
(b) What is the likely extent of environmental stewardship scheme coverage across SW England in the next 10–30 years?
- Should schemes be rolled out across the whole region?
- Should schemes be targeted (e.g. on areas with high flood risk and poor water quality)?

(c) Is water quality a good measure of good rural land management/ farming practice?

Significant legislation is in place to reduce FIO inputs from municipal and agricultural land use, including the Urban Waste Water Treatment Directive (91/271/EEC), Sewage Sludge (use in agriculture) Directive (86/278/EEC), Bathing Water Directive (2006/7/EC), and Shellfish Waters Directive, subsumed within the Water Framework Directive (2000/60/EC) (DEFRA, 2014, 2015). Nevertheless, the frequency of FIO pollution incidents has increased steadily over recent decades (Environment Agency, 2019a).

Livestock slurry is often a major source of FIOs in rural catchments, such as those in SW England (Cefas (Centre for Environment, no date). Research by the National Farmers Union (NFU) and Environment Agency suggests the overall slurry storage capacity on farms is less than 50% of the legal requirements (NFU, 2011; ADAS, 2013). Other sources of animal-derived FIOs include terrestrial and aquatic wildlife populations, which may be significant in some cases. For example, some northern hemisphere estuaries regularly accommodate large populations of several thousand overwintering wildfowl and waders (WeBS, 2017) and cumulative inputs of FIOs can reach x10^{11}-10^{12} colony forming units every 24 h (Davies et al., 1995; Perkins et al., 2016).

Human waste are also likely to be a significant source of FIO contamination in estuaries and coastal waters. Contamination can originate from rural septic tanks and soakaways, which can become a significant risk when multiplied across whole catchments (Environment Agency, 2019a). FIO contamination can also arise from combined sewage overflows (CSOs) that carry both storm water (associated with high rainfall) and untreated sewage. CSO spills are of increasing concern, given the predominance of legacy systems, designed using historic climatic and rainfall data. Recent media attention in the UK has highlighted the vast number of CSO spills relative to the permitted design standards across the country (The Rivers Trust, 2021).

2.1.2. *Persistent Organic Pollutants*

Persistent Organic Pollutants (POPs) can disperse widely and accumulate in food chains, including in farmed shellfish. POPs are derived mainly from industrial and domestic sources and include polychlorinated biphenyls (PCBs) used in electrical and hydraulic equipment, dioxins and polyaromatic hydrocarbons (PAHs) derived from combustion processes, polybrominated diphenyl ethers (PBDEs) used as flame retardants, perfluorinated alkylated substances (PFAS) used in anti-stain and cleaning products and phthalate esters used as plasticisers. EU Hygiene Regulations (European Council, 2004a, 2004b, 2004c) set maximum threshold concentrations for a range of POPs in shellfish meat, including dioxins (4 μg/kg and dioxins + DL-PCBs 8 μg/kg), and the poly-aromatic hydrocarbon (PAH) benzo[a]pyrene (10 μg/kg). The Stockholm Convention (2009) and EU Directives 2008/105/EC and 2013/39/EU also regulate these and other POPs (Beyer et al., 2017).

PBDE concentrations in wild and farmed shellfish in UK coastal waters have previously exceeded the newly imposed Environmental Quality Standard (EQS_{biota}) (based on 6 BDE congenors) of 8.5 ng/kg (2013/39/EU). A decade ago, the concentration of BDE-47 alone ranged from 40 to 450 ng/kg in Pacific oysters (*Magallana gigas*) and 60–160 ng/kg in blue mussels (*Mytilus edulis*) (Fernandes et al., 2009). Following the banning of pentaBDEs (including BDE-47) under the Stockholm Convention (2009), mean concentrations of PBDEs have decreased by ~10% per year in the majority of OSPAR recognised marine areas, including the English Channel and Irish Sea (OSPAR, 2009). However, in the UK in 2020, all freshwater bodies and the majority of transitional and coastal water bodies exceeded the EQS_{biota} for PBDEs (Environment Agency, 2021) and these chemicals continue to present a risk to mariculture.

2.1.3. *Metals*

A range of metals have the potential to cause direct and indirect impacts on the viability of shellfish mariculture, including arsenic, cadmium, lead and mercury, which can bioaccumulate in shellfish and pose a risk to human health. Maximum threshold concentrations in shellfish meat are 1.5 mg/kg for lead, and 1 mg/kg for cadmium according to EU Hygiene Regulations (European Council, 2004a, 2004b, 2004c). OSPAR Environmental Action Criteria (EAC) for mercury (10 μg/kg) and proposed EQSs for mercury (5.7 μg/kg) and arsenic (210 μg/kg) in blue mussels, are substantially lower than background reference tissue concentrations (140 μg/kg mercury; 2503 μg/kg arsenic), indicating environmental risks, including for bivalve shellfish (OSPAR, 2009; Green et al., 2021). Other metals, such as copper, are directly toxic to shellfish and can also impact lower food chain organisms consumed by shellfish. Predominant sources of metal contamination in UK waters are naturally occurring surficial deposits, flooded abandoned mine shafts and metalliferous spoil heaps (Claughton, 2020). Other sources of metals include a range of anthropogenic activities associated with agricultural, industrial and domestic uses, such as crop protection, disinfection and cleaning, wood preserving and antifouling. Inputs of copper from antifouling paint in coastal marinas can elevate local ambient water concentrations by ~2 μg/L copper (Singh and Turner, 2009), potentially exceeding the annual average $EQS_{saltwater} = 5.1$ μg/l, for background dissolved organic carbon concentrations of ~ 2 mg/l).

2.1.4. Agri-chemicals

Agricultural chemicals consist of a wide range of substances, including herbicides, fungicides, insecticides, mollusicides, nematicides, growth regulators and veterinary medicines. A prominent agri-chemical is the insecticide cypermethrin, which is used extensively to manage insect pests on cereals such as winter wheat, fruit and vegetables and also livestock; cypermethrin is also designated as a Priority Substance under the Environmental Quality Standards Directive (2013/39/EU). Cypermethrin is transported downstream with suspended sediments during high rainfall events and is highly toxic at low ng/L concentrations to invertebrates, including molluscan shellfish (Environment Agency, 2007a, 2019c). There is also evidence that chronic low-level exposures to agri-chemical mixtures, including the molluscide metaldehyde, can have significant impacts on bivalve shellfish health, notably on growth (Brooks et al., 2009) and disease resistance (e.g. Pacific oyster herpes virus OsHV-1) (Moreau et al., 2015b, 2015a), and these effects can be augmented by metals (Guéguen et al., 2011; Ogunola, 2017).

2.1.5. Nutrients

Nutrients inputs can cause excess growth of microbial organisms, micro- and macro-algae and macrophytes, which can lead to harmful blooms, eutrophication, oxygen depletion and loss of biodiversity (Diaz and Rosenberg, 2008). Phosphorus (P) typically limits primary production in freshwater ecosystems, while nitrogen (N, in the form of nitrate, nitrite and ammonia) is typically limiting in estuarine and marine ecosystems. However, the balance between N and P limitation can shift depending on local conditions (Guignard et al., 2017) and co-limitation by N and P has been demonstrated across ecosystems in all major biomes (Elser et al., 2007).

N and P inputs are responsible for more UK water bodies failing to achieve good ecological status under the Water Framework Directive compared with all other pollutants, apart from PBDEs (Environment Agency, 2019a). In England, agricultural land is responsible for 50–60% of all Dissolved Available Inorganic Nitrogen (DAIN) inputs to the water environment (DEFRA, 2008, 2015; Parliamentary Office of Science and Technology, 2014). Predominant sources of N and P include chemical fertilisers and livestock slurry. Ammonia, prevalent in aerosol deposition emanating from slurry storage, is also toxic to aquatic life, including farmed shellfish, particularly larval stages of mussels such as *Mytilus edulis* (Kennedy et al., 2017). Other significant land uses which contribute N and P to the water environment include wastewater treatment and rural development (Audit Committee E, 2018).

2.1.6. Suspended solids

Suspended solids derive mainly from soil erosion, runoff from transport systems and remobilisation of river bed sediment during high flow conditions. Suspended solids transport other pollutants including nutrients and agri-chemicals (Parliamentary Office of Science and Technology, 2014; DEFRA, 2014, 2015) and can smother wild and cultured shellfish (Environment Agency, 2019d) or disrupt filter feeding (Ward and Shumway, 2004; Yahel et al., 2009). Agriculture is responsible for 75% of sediment losses to the water environment, however, elevated suspended sediment loads contribute to only around 5% of water bodies failing to achieve good ecological status under the Water Framework Directive (Environment Agency, 2019d).

2.1.7. Emerging contaminants of concern

Emerging contaminants of potential concern for mariculture include pharmaceuticals (both human and veterinary) and personal care products. These contaminants are widespread and originate from domestic, industrial and medical sources. Antimicrobial chemicals are detected widely in river catchments and estuaries dominated by agricultural, urban or mixed land use and, in some cases, may exceed environmentally safe concentrations of circa 0.001 n/L (1 part in 1 trillion) globally, including in the UK (Baker-Austin and McArthur, 2008; Uyaguari et al., 2013). Use of these chemicals in finfish aquaculture may also contribute to exceedances of corresponding EQS values (Langford et al., 2014; Watts et al., 2017). There are now serious concerns about the overuse of antimicrobials and co-selection for antimicrobial resistance in conjunction with metals and pesticides (Watts et al., 2017). Resistance to a diverse range of beta-lactams, aminoglycosides, and other classes of antibiotics has been demonstrated in the pathogen *Vibrio parahaemolyticus*, commonly encountered in estuarine and marine environments and known to accumulate in shellfish and cause of seafood-related gastrointestinal infections in humans (Baker-Austin and McArthur, 2008; Lopatek et al., 2015).

2.2. How is current land use impacting the viability of bivalve aquaculture in SW England?

To evaluate how current land use and land management are affecting the viability of mariculture in South West England, we reviewed published literature and available data sources to identify current land use trends in the region. Our evaluation focused on associations between land use and the evidence for exposure impacts of the key contaminants outlined above, alongside possible mitigation measures and beneficial land management practices.

2.2.1. Current land use in South West England

South West England is largely farmland (80% total land cover), which is dominated by grassland pasture and includes a lower proportion of arable farming than in England as a whole (Fig. 1a). Within the SW River Basin District, land cover currently comprises of improved grassland (53% - lowland pasture treated periodically with fertilisers and herbicides), unimproved grassland (3% - mainly upland); arable land (24%), woodland (11.5%), urban land (6.3%) and wetland mires/peatbogs (2.1%) (Centre for Ecology and Hydrology, 2020). Recent (1990–2019) changes in land cover in SW England (expressed as changing proportion of total land cover) include increasing woodland (9.5–11.5%), (sub)urban land (4.6–6.3%) and arable land cover (20–24%), with concurrent reductions in grassland (66–56%) and wetland (3.1–2.1%) (Fig. 1b).

According to agricultural census data up to 2010 (EDINA, 2020), the reduction in improved grassland cover has resulted from a 40 to 50% reduction in grazing dairy herds (located primarily in SW England) in the last 20 years (Uberoi, 2021). Prior to the recent decline in improved grassland, there was a significant increase in this land type, corresponding with major losses in rough (or Rhôs) pasture in the form of Culm grassland (purple moorgrass *Molinia caerulea* and sharp-flowered

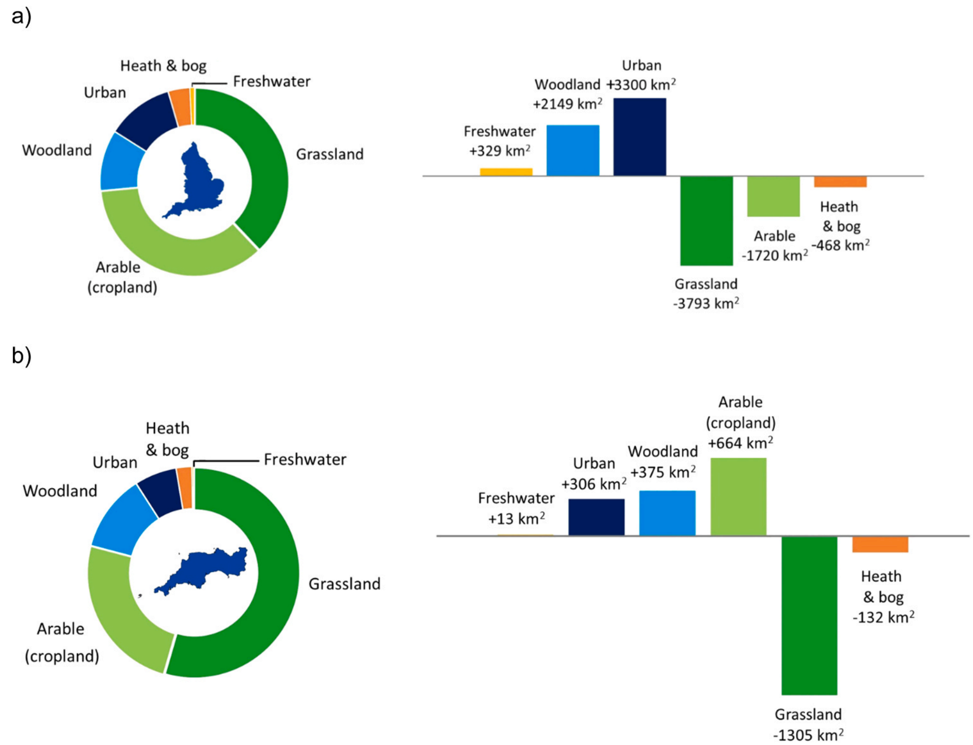

Fig. 1. Current land use in 2019 in a) England and b) the SW River Basin District and histograms showing land use changes from 1990 to 2019, based on CEH land cover mapping (Centre for Ecology and Hydrology, 2020).

rush *Juncus acutiflorus*). Culm grassland is unique to SW England and has been reduced in area by 90% since the 1950s (from 40,000 to 4000 ha), following drainage management and intensive agricultural improvement with fertilisers and pesticides (Puttock and Brazier, 2014; Devon Biodiversity Record Centre, 2016). Culm Grassland is both an internationally important habitat for floral and insect species and provides a range of ecosystem services, including natural flood management (holding 11 times more water than improved grasslands) and water quality regulation (in terms of nitrogen, phosphorus and soil/sediment retention) (Puttock and Brazier, 2014).

2.2.2. The viability of mariculture currently in South West England

Key present threats to the viability of mariculture in South West England include microbial contamination originating from CSOs, extensive grazing of livestock on grassland and from indoor livestock rearing and poor slurry management. Municipal and agricultural sources can be equally important as sources of FIOs, such as *E. coli* and enteric pathogens including *Salmonella* spp. and *Enterococci* spp., whereas norovirus originates primarily from municipal sewage and CSOs. Wildfowl and other water birds also constitute significant sources of faecal coliforms, particularly in the case of large overwintering populations in SW estuaries (CEFAS, 2013). Based on *E. coli* concentrations in shellfish meat, the majority (~90%) of Shellfish Waters in SW England exceed the statutory limit for direct human consumption and are therefore designated as Class B or C waters. This requires operators in these waters to purge (depurate) shellfish in clean water at suitable relay sites or shore-based facilities for up to 48 h, prior to sale for human consumption. The limited number of depuration sites/facilities and the ban on export to European markets of non-depurated UK shellfish (other than from Class A waters) limits ~95% of sales from larger shellfish businesses.

There is high probability for agri-chemicals to enter watercourses in South West England. In particular, acid herbicides applied to improved grassland, such as Mecoprop and 2,4-D are highly water soluble and move rapidly downstream following high rainfall events, intermittently exceeding their respective maximum allowable concentration $EQS_{salt\text{-}water}$ values (Mecoprop 1.7 μg/L; 2,4-D, 0.3 μg/L). These compounds at low μg/L concentrations have been shown to be acutely toxic to phytoplankton, which underpin estuarine and marine food chains and shellfish production (Environment Agency, 2007c, 2007b). Exposure risk is further exacerbated by rigid scheduling for contract herbicide spraying, including during sub-optimal conditions (i.e. during high wind and/or rainfall) (ADAS, 2017).

Persistent organic pollutants in the form of PBDEs were responsible for a number of transitional and coastal water bodies failing to achieve good ecological status in SW England in 2020 (Environment Agency, 2019a) and, due to their persistent nature, they are a significant risk to shellfish mariculture (Fernandes et al., 2009). Other contaminants that may threaten bi-valve culture in SW England include metals such as copper, which can enter SW catchments from numerous abandoned mines and metalliferous spoil heaps (Claughton, 2020). Copper is not particularly toxic to humans or marine mammals and birds that consume shellfish; however, low (marginally above background concentrations (>3 μg/L) can potentially limit shellfish growth and in turn shellfish farm productivity (Strömgren, 1982; Redpath, 1985; Elfwing and Tedengren, 2002). Biocidal products, including copper-based anti--fouling paints used on boats (Singh and Turner, 2009) and historical (banned) organo/tin-based compounds bound to sediments are also likely to add to impact on shellfish located in and around SW ports and marinas. A range of emerging contaminants, including pharmaceuticals and antimicrobial chemicals that are not fully removed during urban wastewater treatment processes, may also impact the viability of mariculture in South West England. However, the evidence base for informing regional or local risk assessments for these chemicals in SW Shellfish Waters is currently limited.

2.2.3. Actions that need to be prioritised to sustain and enhance the viability of mariculture

Enhancing the viability and sustainability of South West England's mariculture businesses will involve both upstream and downstream thinking and likely require both nature-based and engineered solutions (Brown et al., 2020b).

In agricultural settings, up to 90% of contaminants emanate from poor pesticide and slurry handling operations or inadequate farm infrastructure (ADAS, 2017); improvements in pesticide and slurry containment have been highlighted as priorities that most need addressing (NFU, 2011; ADAS, 2013). Other measures for limiting agricultural pollution include managing field treatments, reducing diffuse runoff and improving soil health (soil structure, infiltration capacity and carbon content) through, for example, implementation of 'Catchment Sensitive Farming - CSF' and 'Farming Rules for Water' (UK Government, 2018). Across CSF priority areas (37% of farmland) farm infrastructure and livestock measures have significantly reduced FIO concentrations in water courses (−91% combined), manure and fertiliser management measures have substantially reduced dissolved phosphorus (−68% combined) and pesticide management has reduced local pesticide concentrations (−88%), while soil management measures have reduced suspended solids (−90%), total phosphorus (−60%) and nitrogen (−45%) (Natural England, 2019). CSF/Countryside Stewardship schemes and Catchment-based approaches (CaBA) also advocate pollution control via natural flood management, including tree planting, creation of riparian buffer strips and restoration of wetland areas. In the last 10 years the South West Water's Upstream Thinking partnership with SW Farmers and conservation group has restored 2083 ha of wetland/peatland in 10 catchments across Exmoor, Dartmoor and Bodmin moor and reduced storm discharges by up to 32% (South West Water, 2020).

In urban settings, the management of CSO spills by water companies is being prioritised by upgrading of sewage and drainage infrastructure to cope with both urban development and increasingly frequent and prolonged high intensity rainfall events. In rural developments the export of FIOs through discharges from septic tanks or soakaways (comprising 1.25 million properties in England) is a potential risk for many South West (sub)catchments (Environment Agency, 2019a). Systems discharging directly to the water environment were made illegal in the UK in January 2020, however, it is anticipated that a large number of legacy systems are likely to remain active into the foreseeable future.

2.3. How future conditions are likely to affect the viability of mariculture in SW England

Given that water quality and mariculture viability are heavily dependent upon land use and land management in surrounding catchments, we explored current trajectories for national and regional land management policy and their impacts on mariculture. Key policy drivers include the UK's 10-year National Energy and Climate Plans, National Food Strategy, National Planning Policy Framework (NPPF), Industrial Strategy, Clean Growth Strategy and the 25 Year Environment Plan (HM Government, 2017a, 2017b, 2018). The UK Government's 25 Year Environment Plan aims to achieve net zero carbon emissions and net gains in biodiversity and water quality in England by establishing 'Environmental Land Management Schemes' for farmland, increasing woodland cover from 10% to 12% across England and creating a 'Nature Recovery Network' to return 75% of protected sites (including freshwaters) to favourable condition (HM Government, 2020a).

In addition to considering policy drivers, our stakeholder analysis and development of the following future scenarios also took into account climate change, which has been reported to pose one of the greatest risks to future food production both in the UK and globally (Roy and George, 2020). Stakeholders agreed that the principal risk to mariculture viability resulting from climate change will be an increase in the intensity and frequency of rainfall events, which will increase potential pathways for contamination through connecting catchment runoff to watercourses. This is of particular concern regarding connecting diffuse agricultural pollution, urban runoff, as well as through increasing the spill frequency of CSOs. Changing patterns of rainfall, including increased risk of drought in the summer and flooding in the autumn and winter are expected to impact on crop production and the timing of farming operations, resulting in increased soil erosion and compaction.

2.3.1. 'Business-as-usual' scenario

The business-as-usual scenario represents the current expected trajectory of land use changes (expressed as % of total land cover in the SW River Basin District), based on trends from the past 30 years (1990–2019, shown in Fig. 1b). This scenario aligns with the 'go with the flow' scenario outlined in the UK National Ecosystem Assessment (UK NEA, 2014). Projection of current trends highlights a continued loss in agricultural grassland (−7.5%), in conjunction with increasing arable land (+4%), woodland (+2%) and urban land cover (+1.5%). The projected increase in urban land cover from 6.3% to 7.8% is in line with the ~20% population increase (projected by South West Water for 2039). Farmland management is not expected to change significantly from current levels and extent of farm engagement under Countryside Stewardship (currently covering 37% of farmland in England) (Environment Agency, 2019b). Therefore, it is expected that remedial measures for improving water quality, including implementation of Catchment Sensitive Farming (CSF) 'farming rules for water' and tree planting under schemes such as 'Woods4Water' (Woods4Water, 2020) will continue to be targeted in CSF priority areas. These measures, in combination with moderate increases in arable land and declining pasture and grazing cattle herds, are expected to have moderately positive impacts in terms of alleviating flood-related pollution risks for rural and urban watercourses in South West England.

2.3.2. 'Working with nature' scenario

Under this scenario regenerative farming practices are anticipated to extend across SW catchments: e.g. cover cropping, no-tillage, reduced pesticide use, integrated nutrient and pest management, integrating crops with trees, livestock and natural flood management (Lal, 2020). This extensive, regenerative agriculture will be enabled through implementation of Environmental Land Management Schemes and Nature Recovery Networks under the 25 Year Environment Plan and by propagating best practice, profiled for farms in England, including SW England (Agricology, 2021). The UK's Industrial Strategy and the accompanying Clean Growth Strategy also call for land use management to deliver multi-functional, sustainable agriculture (HM Government, 2017b, 2017a). Technical innovations in precision farming methods are expected to contribute towards clean growth, enabling reductions in fertiliser, pesticide and irrigation water use, through environmental sensing and surveillance systems and more targeted use of agri-chemical and recycled nutrient-rich waste products (Roy and George, 2020). By increasing soil health e.g. through reduced tillage and cover cropping, precision farming and regenerative farming methods will also help mitigate the impacts of climate change regarding agricultural run-off and soil erosion. To further mitigate climate impacts agricultural and urban development will accommodate sea level and floodplain expansion through managed realignment. This scenario is consistent with the 'nature at work' scenario outlined in the UK National Ecosystem Assessment (UK NEA, 2014) and is likely to significantly benefit mariculture in South West England by minimising FIO and agri-chemical contamination of watercourses.

2.3.3. 'Going against the flow' scenario

This scenario is the antithesis of 'working with nature' and represents a possible worst-case scenario in which there is large-scale abandonment of agricultural land following the removal of farming subsidies and limited uptake of Environmental Land Management Schemes. This results in the intensification of farming on only the most productive agricultural land, including lowlands and riparian corridors. Growing intensification of these agricultural hotspots, combined with increasing trends for dairy and beef cattle to be reared indoors and fed fodder crops, such as maize and beet grown on former pasture land, is expected to increase soil erosion and run-off, significantly impairing water quality (Environment Agency, 2019b). These anticipated outcomes are the same for increased vegetable cultivation required to supply the growing vegetarian food market. At the same time, climate impacts on agricultural and urban development and storm water management are exacerbated by sea level rise and floodplain expansion due to inadequate planning and managed realignment.

2.3.4. 'Rush for renewable energy' scenario

Significant growth in renewable energy is required to meet the UK's goal of achieving net zero greenhouse gas emissions by 2050. Key growth areas include: carbon neutral perennial biomass/energy crops; wind farms; solar farms. This scenario aligns with the 'national security' scenario outlined in the UK National Ecosystem Assessment (UK NEA, 2014). The UK's draft integrated National Energy and Climate Plan (NECP) calls for expansion and increased renewable energy production from onshore (and offshore) wind farms and solar farms in the next 10–30 years (Easy et al., 2011; BEIS, 2019; DEFRA, 2019b). The impact of increasing South West England's renewable energy capacity on water quality and the viability of mariculture will depend upon the energy generation mix selected. Prioritising solar and wind farms, which enable livestock to continue grazing around sites is likely to result in minimal changes in FIO and agri-chemical export. The environmental consequences of continuing to rely on biomass-based energy generation strategy are dependent on which crops are cultivated. Biomass crops (mostly imported) currently generate ~50% of renewable electricity and ~80% of renewable heat in the UK. Maize is the largest domestic energy crop with 31% of UK maize (64,000 ha) being grown in SW England (DEFRA, 2020a). Maize cultivation causes soil erosion and has a net positive carbon footprint with or without tillage. Current cultivation of perennial biomass crops elephant grass (*Miscanthus* spp. ~1500 ha) and short rotation coppice (poplar and willow ~600 ha) have significant potential to expand on low grade agricultural land and can help mitigate flood risk (DEFRA, 2019a).

2.3.5. 'Extensive tree planting' scenario

The Government's 25 Year Environment Plan commits to natural woodland restoration and tree planting to increase woodland cover to 12% across England (planting up to 30,000 ha of trees per year by 2025), which will contribute significantly to national efforts to reach net zero carbon emissions by 2050. Woodland restoration will be achieved through the £ 640 m Nature for Climate Fund (NCF) announced in the March 2020 budget. In order to maximise the delivery of public goods through the spending of public money, the forthcoming Tree Strategy for England (undergoing public consultation) aims to align tree planting with nature conservation, avoiding tree planting on carbon sequestering wetland/peat bog. The strategy aims to target planting in urban areas, integrate trees and woodlands into farmland and create large new forests (DEFRA, 2020b). The Forestry Commission and Environment Agency's £ 1.4 million 'Woodlands for Water' programme (funded via the NCF) aims to plant over 850,000 trees to protect around 160 km of river from flooding and impaired water quality by reducing surface run-off (HM Government, 2020b). In SW England the 'Woodlands4-Water' scheme will plant over 30,000 trees in three areas: the Taw Torridge catchment including the North Devon Biosphere; the Camel catchment in Cornwall; the Otter, Sid and Axe catchments and the Blackdown Hills Area of Outstanding Natural Beauty (AONB) in East Devon (Woods4Water, 2020). Tree planting is being targeted based on opportunity mapping, which aims to identify priority locations to restore environmental system function, avoid unintentional consequences and promote more integrated catchment management (Forest Research, 2020; LAGAS, 2020). Tree planting, particularly along riparian corridors, is likely to reduce run-off and flooding by increasing rainfall interception and soil infiltration, thus improving water quality and the viability of mariculture. However, as with renewable energy generation, the environmental consequences of tree planting will be context dependant, including which species and locations are prioritised.

2.3.6. How can we practically implement our findings for future research?

Predicting likely water quality impacts (positive and negative) associated with plausible alternative future land use, land management and climate change scenarios may provide insights for refining and targeting environmental policy development and implementation, and possible use, for example, as part of the UK's 5-year Green Recovery Challenge and the 25-year Environment Plan. The scenario building and stakeholder integration presented here is a first step towards this for SW England, and strengthens the ability for strategy development through identifying, evidencing and delimiting the systems boundaries and stakeholder engagement of predominant likely scenarios. The complexity of multiple land and water system interactions, however, makes definitive recommendations challenging currently. Practical implementation will require further evaluations encapsulating key stakeholders and scenarios, monitoring and data collection to evidence and steer decisions, and iterative evaluation to monitor success. This needs to take place at both regional and national scales.

The next step in this process is developing scenario-based modelling and subsequent monitoring to establish baselines and evidence for design, implementation, and evaluation of policy for pertinent water quality criteria and key land uses. Addressing this data gap is essential for prospectively evaluating the effectiveness of policies involving both financial incentives (e.g. ELMS and Woodland grant schemes) and rule-based environmental regulation (e.g. Environmental quality standards under the WFD, and CSF farming rules for water). In any event, monitoring environmental changes (input and output parameters) accurately with respect to robust benchmarks will be critically important for evidencing/confirming improvements in water quality.

Comprehensive understanding of scenarios and evaluation at scale can then be progressed towards spatially explicit policy and regulation of land use, designed to promote aquaculture alongside other environmental targets, such as biodiversity, air quality and greenhouse gases. This is likely to be a lengthy process, particularly when defining multiple interacting land and water systems; however, integrating systems will develop environmental regulation from a targeted approach, through to holistic regulation, for example through connecting regional strategies such as Marine Spatial Plans and Aquaculture Strategy upstream towards land used throughout a catchment.

In summary, ensuring positive, sustainable change in the way we manage land and water, including for food-production, requires an iterative and inclusive stakeholder approach. The participative regional approach we have taken to develop broad consensus stakeholder views on possible future scenarios for land use/management in SW England is a crucial first step in achieving this.

4. Conclusions

Greater consideration needs to be directed towards managing the land – water interface, ultimately allowing the full potential of water- and land-based food production systems in the UK to be realised. Improving water quality through better land management is essential for improving consumer safety and confidence, so that bivalve aquaculture can become a thriving industry in SW England and contribute significantly to UK food security and sustainable regional and economic development.

Land use strongly influences water quality at both local and broader catchment scales, extending to coastal waters and potentially affecting mariculture. This is particularly the case for the farming of filter feeding bivalve shellfish, which can accumulate significant quantities of waterborne contaminants. Many of the contaminants that most affect shellfish derive from diffuse inputs, including fertilisers and pesticides from agriculture land and livestock, as well as from the use and disposal of chemicals and municipal sewage effluents via point source discharges.

This highlights the potential conflicts between land use, including land-based agricultural food production, and marine-based aquaculture food production. Faecal contaminants derived from livestock slurry and municipal sewage are currently the greatest contaminant threat to the viability and sustainability of the UK shellfish farming industry.

The relationship between land use and water quality indicates that the ongoing viability of bivalve mariculture in SW England, and in many other UK and global areas, will be determined by future land use management practices and environmental policy developments, which urgently need to ensure improvements in water quality to minimise contaminant exposure. Taking a whole catchment modelling approach by working with cross-sector stakeholders active in SW England (and with relevance to other regions around the globe with similar land uses), we have identified a range of future land use/ land management scenarios pertinent to the future development and sustainability of bivalve mariculture. We recommend that these scenarios are applied as the basis for this much needed future research, modelling and comprehensive systems analysis of the synergies and trade-offs regarding future policies to optimise land use, land management and water quality.

CRediT authorship contribution statement

James L. Webber: Conceptualization, Investigation, Formal analysis, Methodology. **Charles R. Tyler:** Conceptualization, Investigation, Formal analysis, Methodology. **Donna Carless:** Visualization, Formal analysis. **Ben Jackson:** Investigation. **Diana Tingley:** Investigation. **Phoebe Stewart-Sinclair:** Visualization, Formal analysis. **Yuri Artioli**: Investigation. **Ricardo Torres**: Investigation. **Giovanni Galli**: Investigation. **Peter I. Miller:** Investigation. **Peter Land:** Investigation. **Sara Zonneveld**: Investigation.Melanie **C. Austen**: Investigation. **A. Ross Brown**: Conceptualization, Investigation, Formal analysis, Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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