

Harmful Algae

An Approach for Evaluating the Economic Impacts of Harmful Algal Blooms: the Effects of Blooms of Toxic *Dinophysis* spp. on the Productivity of Scottish Shellfish Farms --Manuscript Draft--

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Abstract:	<p>Shellfish production is an important activity for the economy of many countries. As well as its direct value, it helps to stabilize communities in rural areas characterized by limited job opportunities. It is also important for consumers who recognize shellfish as a healthy product that gains its nutrition from natural plankton without the need for fertilizers, chemical treatments or other anthropogenic intervention typical of terrestrial agriculture or other marine aquaculture. Nevertheless, global shellfish fisheries are under threat from harmful algal blooms (HABs) and related biotoxins, whose production is potentially exacerbated by global changes. This research provides evidence of economic impacts on Scottish shellfish farms in the last 10 years caused by HABs and their associated biotoxins. In contrast to previous approaches that have focused on variation in production as a function of temporal trends and blooms events, we use a production function approach to show which input factors (labour, capital, climate variables, concentration of biotoxins) have an effect on production. Results show that diarrhetic shellfish toxins produced by the genera <i>Dinophysis</i> are most significant. A 1% change in the production of these biotoxins reduces shellfish production by 0.66%, with an average yearly negative variation in production of 15% (1,080 ton) and an economic loss (turnover) of £ (GBP) 1.37 m per year (in 2015 currency) over a national annual industry turnover of ~ £ 12 m. The production function approach is coupled with a multivariate time series model (VAR) capturing the statistical relationship between algal concentration, information on climatic variables and biotoxins to forecast the damage to shellfish production from HABs. This provides producers and regulators with the economic information to plan temporal and spatial mitigating measures necessary to limit damages to production by comparing the costs of these measures with the costs of lost production.</p>

Dear Editor,

We are pleased to re-submit to your Journal a revision of the manuscript **HAR_ALG-S-20-00039R1**, titled "*An Approach for Evaluating the Economic Impacts of Harmful Algal Blooms: the Effects of Blooms of Toxic Dinophysis spp. on the Productivity of Scottish Shellfish Farms*".

We have reviewed all the sections of the paper to address the questions raised by the reviewer, which mainly regarded its readability. There are not technical changes in terms of methodology and results. However, the paper has been rewritten in many sections, following the suggestions provided, and tightened. Repetitions have been removed and grammar checked. Overall, this has provided a much shorter document that is now 400 words less than the previous version.

Hoping that this revised manuscript fits the requirements of the reviewer and the interests of your Journal. On behalf of my co-authors I send through my best regards

The corresponding author,

A handwritten signature in blue ink that reads "Simone Porfiri". The signature is written in a cursive style.

York, 1th October 2020

Reviewers' comments:

Reviewer #1: This is a good revision, but it needs just a little more work before it can be accepted.

We thanks the reviewer for the comments provided that will improve the readability of the manuscript. We have accepted almost all ideas proposed; where some suggested are not accepted, this is specified and reasons are provided. In particular, we have restructured the whole manuscript, removing duplication, tightening sentences and reducing globally 400 words.

Please carry-out the following:

Line 344: remove "for the first time". This is for readers to observe themselves, not for you to tout.

We changed as suggested

Line 346: "...generated by genera..." sounds awkward.

We changed generated in produced

Line 353: Remove "the" in front of "regulators". In general, there is a misuse (presence or absence) of articles (the, a, an) throughout. The entire paper needs to be gone through carefully so that it reads well. Removed "the".

The use of articles in the paper has been revised.

Lines 367-368: delete "and provides an important social impact by"

We removed the full sentence to avoid repetition with a statement reported at lines 376-379.

Line 425: define or use another term for "eco-economic".

We changed it to ecological and economic

Line 444: replace "subdue" with "levels subside".

We changed as suggested

Line 496: terminology is getting mixed here "input of the production function". Literally, the VAR is being used to instrument a variable that is a Cobb-Douglas factor input (actually an unproductive one).

Sentence reformulated to be clearer at lines 491-498. We have reformulated as below proposed:

The production function is preceded by a multivariate time series statistical approach (vector autoregression-VAR) to forecast the impact of biological and climatic variables on the production of biotoxins. Although the two models are independent, the VAR can be used to

instrument biotoxins in the production function to forecast the expected impacts on shellfish production. Before moving to the details of the statistical approach and results, a brief description of the Scottish shellfish industry, along with the effects of climatic, environmental and biological factors on shellfish production is reported.

Line 510: the map is excellent. Thank you! Sure would like to see the sampling locations and mussel licenses located on it...

Number of sampling points is the only information available to us as reported by Marine Scotland. Moreover, we do not present the of sampling points and mussel licences as there has been some locational changes in these over the multi-year duration of the study and hence cannot be mapped in a way that is useful to the reader. To report a bit more information on the number of samples and where they occur we added the following text at line 509:

Figure 1 provides a map of all the marine Scottish regions, but not the geolocation of the sample². Our study refers only to the shellfish production region of the Shetland Islands and the Western marine regions (Outer Hebrides, West Highlands, Argyll and Clyde).

² Marine Scotland reports the number of farms sampled in the annual publication "Scottish Shellfish production Survey", available at the following web site: <https://www.gov.scot/collections/scottish-fish-farm-production-surveys/>. In 2019, 129 businesses were sampled, distributed as follows: 44 in the West Highlands, 5 in the Orkney Island, 23 in the Shetland Islands, 43 in the Clyde, and 14 in the Outer Hebrides. Consulted on 21st August 2020

Line 541: Replace "most cultured" with "seafood product that is cultured more than any other" or something like that.

We replaced "most cultured" with "dominant shellfish product"

Lines 550-553: this explanation is unclear. If you are referring the estimation of the production function, then the effect is not strictly a marginal effect (its a percentage change in production when DSP exceeds the threshold).

Part of the sentence has been moved to an early section and any reference to marginality is demanded to the specific section about the explanation of the production function (*methods*).

Lines 641-657: I think this discussion could be left out (except for the variable definitions) and just start with the transformed function.

We have simplified this section removing the text that can be considered redundant. However, we prefer to present the full set of equations...this can be easier to follow for the audience that is not familiar with the Cobb-Douglas model.

Lines 647-650: It's unclear what the difference is between HAB and BTX. Does the cell threshold match the bio-toxin threshold, so that they are actually the same variable?

Both vectors are measured as frequency above a threshold, as described at line 599-605. The two sets of variables are not the same. HAB is a fraction (0-1) above threshold

concentration of algae, while BTX is fraction above threshold concentration of biotoxins. This is also specified at line 642-645.

Lines 710-742: The descriptive statistics should be in the data section.

I have always reported descriptive statistics in the result section. This is part of the analysis of data. Thus, we prefer reporting it in the result.

Line 743: I think it would be more useful to title this section "First Stage" or something like that. You can just say that you used a VAR to instrument for DSP.

VAR and production function are two separated models that are meaningful as single entity. However, it is also possible to use the VAR to forecast with 1-year lag the expected DSP, and then the latter figure can be multiplied by the beta coefficient of the DSP variable in the production approach to calculate the expected damage in shellfish production. We think that there is no need to change the title to the section.

Line 748. Dependent

Yes, thanks for spotting the mistakes.

Line 756: "explicative"?

Thanks for spotting the mistake; we wanted to say "explained" variance

Line 783: Then this is the Second Stage.

As mentioned above, this can be seen as a second stage. However, we do not want to give the idea that the two things need to be run in serial way. Therefore, we prefer avoiding any reference to the terminology "first and second stage". We decided to keep the title as it is. However, it is explained how the two models can be used jointly.

Lines 797-798 and 926-927: You're letting the model, not the data talk here. You cannot just pass this off so blithely. This result may be due to the lower ratio of labour to capital in the Shetland Islands (lines 563-564; lines 716-717). So it may be an indication that the mussel culturing in the Shetlands is technologically different from mussel culturing in the other regions.

Thanks for the interesting comment. What we aimed to do in this part of the paper was to explain the results of the models proposed, without providing any specific comment. It is possible that the explanation proposed by the reviewer is correct. However, both models (random and fixed effect) show that labour is not economically meaningful. A neutral consideration to make here (reported in the manuscript) is that shellfish farming has reached the highest level of productivity given the capital employed (according to the law of marginal diminishing return,) i.e. one unit more of labour does not contribute to the increase in productivity. We added also a footnote stating that the regression analysis performed without data from the Shetlands Island provides no significant results for both the variable capital and labour. These results are shown at the end of this document only for the reviewer. This is due to the limited variability of the database. We conclude that the higher intensive capacity of the Shetland influence the result of capital, but do not make any difference in the interpretation of the variable labour. It is also possible that the capital and labour variables

used are not the most effective (this is mentioned as a limit in the discussions). These considerations are reported at lines 774-787.

Line 849: Insert "(lost gross revenues)" after damage.

Added

Lines 856-864: Good job. I think you handled the discussion of the welfare effects well here.

Thanks a lot

Lines 895-896: It's unclear what is being argued here. Please elaborate.

Sentence completely reformulated at lines 859-863.

The Cobb-Douglas approach, as it considers capital as input factor, is able to include more explicitly farmers behavioural as captured by the varying number of sites of production in order to anticipate production under the alert of HAB event. This cannot be modelled in the dose response model (Jin et al., 2008; Rodriguez et al., 2011).

Lines 911-913: This is the most interesting implication of the results. This is unclear, and it needs to be fleshed out more. This is why your research is policy-relevant, and why it's not just an econometric exercise. What are the implications for the regions other than the Shetland Islands? If they are hit harder by BTX and less productive, what are the implications for their sustainable development moving forward?

The sentence has been rewritten and expanded from line 866-874.

These results offer insight into regional differences in operation and the environmental characteristics of the sites. Although not an object of this study, we can say that studying the productivity in the different regions would allow more informed management to support the sustainable development of the shellfish industry. In the West Highlands, characterized by a lower productivity, the impact on production is marginally more damaging than in the Shetlands, suggesting managers may be able to put in place strategies to minimize the impacts of harmful algae, from shifting production sites to rearranging contractual agreements with wholesalers and retailers.

The paper still reads like an early, unpolished draft. It needs to be gone through carefully to get the descriptions, presentations of data, methods, and results, and discussion tightened up (I would prefer using the passive voice), and to reduce duplication.

We removed duplications and tighten up the overall manuscript, cutting more than 400 words. The use of articles has been revised too.

Fixed effect model

Instrumental variables (2SLS) regression Number of obs = 30

Wald chi2(6) = .

Prob > chi2 = .

R-squared = .

Root MSE = .24594

	Coef.	Std. Err.	z	P>z	[95% Conf. Interval]	
oadtxsptxs	-1.044743	.5285439	-1.98	0.048	-2.08067	-.0088155
sites	.4286133	.4363633	0.98	0.326	-.426643	1.28387
labour	-.0788998	.4598259	-0.17	0.864	-.9801421	.8223425
clyde	5.82994	3.211255	1.82	0.069	-.4640029	12.12388
outerheb	5.764827	2.497049	2.31	0.021	.8707015	10.65895
highland	5.910662	2.92157	2.02	0.043	.1844904	11.63683

random effect model

G2SLS random-effects IV regression Number of obs = 30

Group variable: region2 Number of groups = 3

R-sq:

within = 0.4077

between = 0.7907

overall = 0.4447

Obs per group:

min = 10

avg = 10.0

max = 10

Wald chi2(1) = 36.87

corr(u_i, X) = 0 (assumed) Prob > chi2 = 0.0000

(Std. Err. adjusted for 3 clusters in region2)

	Coef.	Std. Err.	z	P>z	[95% Conf. Interval]	
oadtxsptxs	-.9750449	.1620368	-6.02	0.000	-1.292631	-.6574586
sites	.4420955	.4404011	1.00	0.315	-.4210748	1.305266
labour	-.0193734	.181864	-0.11	0.915	-.3758203	.3370736
_cons	5.525288	.6835417	8.08	0.000	4.185571	6.865005

sigma_u 0

sigma_e .27497266

rho 0 (fraction of variance due to u_i)

Highlights

- Economic impacts of harmful algae on Western Scottish shellfish aquaculture are assessed.
- The Cobb-Douglas production function is used to model these impacts.
- A 1% change in diarrhetic shellfish toxins is found to reduce production by 0.66%.
- Annual losses from *Dinophysis* generated biotoxins are estimated at 15% of total production (equivalent to £1.37 m/year in 2015 GBP).
- Such information is of use to industry to evaluate the cost/benefit of HAB mitigation measures.

312 **An Approach for Evaluating the Economic Impacts of Harmful Algal Blooms:**
313 **the Effects of Blooms of Toxic *Dinophysis spp.* on the Productivity of Scottish**
314 **Shellfish Farms**

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322

323 **Highlights**

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325 assessed.
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329 production (equivalent to £1.37 m/year in 2015 GBP).
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332

333 **Abstract**

334 Shellfish production is an important activity for the economy of many countries. As well as
335 its direct value, it helps to stabilize communities in rural areas characterized by limited job
336 opportunities. It is also important for consumers who recognize shellfish as a healthy
337 product that gains its nutrition from natural plankton without the need for fertilizers,
338 chemical treatments or other anthropogenic intervention typical of terrestrial agriculture or
339 other marine aquaculture. Nevertheless, global shellfish fisheries are under threat from
340 harmful algal blooms (HABs) and related biotoxins, whose production is potentially
341 exacerbated by global changes. This research provides evidence of economic impacts on
342 Scottish shellfish farms in the last 10 years caused by HABs and their associated biotoxins. In
343 contrast to previous approaches that have focused on variation in production as a function
344 of temporal trends and blooms events, we use a production function approach to show
345 which input factors (labour, capital, climate variables, concentration of biotoxins) have an
346 effect on production. Results show that diarrhetic shellfish toxins produced by the genera
347 *Dinophysis* are most significant. A 1% change in the production of these biotoxins reduces
348 shellfish production by 0.66%, with an average yearly negative variation in production of
349 15% (1,080 ton) and an economic loss (turnover) of £ (GBP) 1.37 m per year (in 2015

350 currency) over a national annual industry turnover of ~ £ 12 m. The production function
351 approach is coupled with a multivariate time series model (VAR) capturing the statistical
352 relationship between algal concentration, information on climatic variables and biotoxins to
353 forecast the damage to shellfish production from HABs. This provides producers and
354 regulators with the economic information to plan temporal and spatial mitigating measures
355 necessary to limit damages to production by comparing the costs of these measures with
356 the costs of lost production.

357

358 **1. Introduction**

359 *1.1 Background and aim of the study*

360 Culture of bivalve molluscs is an important commercial activity in Europe, with a production
361 of ~ 625k tonnes and value of EUR 1.24b in 2017 (European Union, 2019). Europe wide,
362 mussel species exhibit the highest volume (35%) of farmed bivalves species, with a total EU
363 production of 129,500 tonnes by 2017 (European Union, 2019). Shellfish farming is carried
364 out predominantly by small family enterprises (STECF, 2018) and is important for many rural
365 areas of Europe, including the Scottish Highlands where it generates a gross value (turnover)
366 of £ 12.4m (Highlands and Islands Enterprise and Marine Scotland, 2017). In Scotland, it is
367 undertaken by 205 separate enterprises generally located in rural coastal areas.

368 Blue mussels dominate shellfish production in Scotland (~ 96% by weight - MSS, 2018) with
369 a value (turnover) of £ 10.1 m in 2017 (Highlands and Islands Enterprise and Marine
370 Scotland, 2017; Munro and Wallace, 2018). The whole of Scotland's shellfish aquaculture
371 supply chain also contributes £ 25.9 m of associated earnings and £ 50 m of gross value
372 added (average for 2014 and 2015) (Highlands and Islands Enterprise and Marine Scotland,

2017). While the value of the Scottish shellfish production in comparison with other industries is relatively small, its geographical location in remote communities characterized by few other employment opportunities makes it very important for the sustainable development of the rural economy. This is evident from the Scottish Government's support for the Scottish aquaculture industry's plans to double its economic value and the number of jobs it generates by 2030. However, to achieve this, it is important to have an accurate economic valuation of the different factors, such as harmful algal blooms (HABs), that are limiting current production and future expansion.

Globally, there is a positive market perception towards shellfish as an "environmentally healthy product" that gains its nutrition from natural plankton within the water column. This is because shellfish culture occurs without the need for fertilisers or chemical treatments typical of terrestrial agriculture or other marine aquaculture (Newell et al., 1989, Scotland's Aquaculture, 2020), with shellfish ingesting particulate matter in the water column. However, the mode of nutrition exhibited by these filter feeding bivalves makes them vulnerable to contamination by biotoxins produced by certain harmful algal species, with associated implications for human health (Smayda, 1990; Berdalet et al., 2016), but also for the economic sustainability of the industry (Davidson et al., 2014).

In Scottish waters Diarrheic Shellfish Poisoning (DSP), Paralytic Shellfish Poisoning (PSP) and Amnesic Shellfish Poisoning (ASP) are the shellfish toxicity syndromes of greatest concern (Davidson et al., 2011; Davidson and Bresnan, 2009). PSP toxins produced by the genus *Alexandrium* are regularly detected in mussels during the summer months (Bresnan et al., 2008). DSP toxins are more frequent still, often as a result of the advective transport of the causative *Dinophysis* to coastal aquaculture (Whyte et al., 2014; Paterson et al., 2017), with

396 *Prorocentrum lima* being another source of these toxins. *Pseudo-nitzschia* mediated ASP is
397 less frequent (Rowland-Pilgrim et al., 2019) and may also require advective cells transport
398 (Fehling et al., 2012). Azaspiracids (AZA) produced by the genus *Azadinium* (Tillmann et al.,
399 2009) and yessotoxins (YTX) produced by the dinoflagellates *Protoceratium reticulatum* and
400 *Lingulodinium polyedrum* also occur.

401 To ensure shellfish safety for public consumption, EU regulation EC No 853/2004 (European
402 Union, 2004) requires the monitoring of the concentration of biotoxins in shellfish flesh and
403 their causative harmful phytoplankton. In Scotland, monitoring is overseen by the
404 competent authority Food Standards Scotland (FSS) and carried out by the Centre for
405 Environment, Fisheries and Aquaculture Science (CEFAS) for biotoxins and the Scottish
406 Association for Marine Science (SAMS) for phytoplankton. Sampling is undertaken weekly
407 during spring and summer, and fortnightly in winter and autumn at a set of representative
408 monitoring points with the aim of minimising the risk of not detecting above regulatory
409 threshold shellfish biotoxin concentrations (Holtrop et al., 2016). However, while
410 considerable effort is, quite understandably, expended to ensure shellfish safety, the impact
411 of HABs on the economic sustainability of this regionally important industry remains
412 unquantified. An economic assessment of the impact of HABs on the Scottish shellfish
413 industry will therefore allow the financial assessment of alternative mitigation and
414 management strategies for alleviating revenue losses in a HABs scenario.

415 There is an important literature on the valuation of harmful algal bloom (HAB) impacts in
416 sectors like commercial and recreational fisheries, tourism and recreation and public health
417 just to mention a few (Sanseverino et al., 2016; Groeneveld et al., 2018; Adams et al., 2018).
418 The majority of these studies refer to physical and economic impacts observed in the US,

419 with few studies from other regions (Adams et al., 2018). Studies of the economic impacts
420 of HABs on aquaculture elsewhere are sparse, although Park et al. (2013) provide an
421 example from Korea. Research on shellfish and finfish aquaculture in Europe is equally
422 limited, with exceptions being the study of the impact of *Alexandrium* species on Galician
423 (Spain) mussel farming, measured by correlating HAB incidence with industry metrics
424 (Rodriguez et al., 2011). Ecological and economic consequences for the shellfish farming
425 sector have been also addressed in Bourgneuf Bay (France) by an input-output (IO) analysis
426 (Agundez et al., 2013).

427 A first attempt to provide analysis of the economic impact of HABs on several marine
428 sectors in the US was made by Hoagland et al. (2002), with further research addressing
429 more specifically the effect of HABs in sectors like commercial fisheries (Hoagland and
430 Scatasta, 2006; Jin and Hoagland, 2008; Jin et al., 2008), recreational fisheries (Hoagland and
431 Scatasta, 2006; Dyson and Huppert, 2010) and tourism (Hoagland and Scatasta, 2006; Taylor
432 and Longo, 2010; Morgan et al., 2011). However, results of these studies are not necessarily
433 comparable, because they are based on different and incommensurable metrics (Davidson
434 et al., 2014). Some of them, for instance, measure direct impacts to the business and
435 indirectly to the supply chain (by IO analysis), and are therefore not relevant for measuring
436 benefits of policies through cost benefit analysis (for a list of recent studies implementing IO
437 analysis, see Adams et al., 2018). Globally, studies make use of lost sales (gross revenues or
438 turnover) (see Hoagland et al., 2002 for an example), while it is uncommon for the analysis
439 of welfare measure such as consumer and producer surplus to be used as appropriate
440 measures of cost of HAB to society¹. Although lost revenues are commonly assumed as a

¹ Consumer surplus is the difference between the price that consumers are willing to pay (WTP) and the price they pay. Producer surplus is the difference between the price received by producers and the cost of production (the minimum willingness to accept - WTA).

441 proxy of economic welfare, this is true if the quantity of product that cannot be
442 commercialized has been harvested and processed, but not sold. If the product is sold after
443 the biotoxin levels subside, the gross revenue lost is overestimating the welfare lost by the
444 producer. Furthermore, economic impacts are often based on a retrospective analysis of the
445 average reduction in production following an algal bloom event, therefore implicitly
446 inferring that reduction in production is exclusively caused by the HAB (this allows
447 calculation of the average impact of the HAB on production) (Jin et al., 2008). Conversely,
448 there is the need of an *ex ante* valuation of marginal expected damages caused by HABs,
449 separating them from the impacts determined by other causes (e.g. changes in
450 management and impacts of environmental-climatic variables), and to facilitate the
451 comparison with the cost of measures reducing the risk from algal production.

452 An interesting approach that relates changes in environmental properties and damage to a
453 marketed product is the dose response model, which measures the marginal damage in
454 production caused by a specific environmental effect. The latter value can be simply
455 multiplied by the unit price of the affected product to estimate the lost value (we are
456 making the assumption that price does change after the environmental effect; this condition
457 applies for relatively small changes in production). An example of a dose response model
458 applied to HABs is provided by Jin et al. (2008) who assessed the impact of a red tide on
459 commercial shellfish fisheries in Maine and Massachusetts. They compared revenues during
460 the event and in previous years to estimate the average production change incurred. Then,
461 to infer marginal impacts of the red tide on production, these authors performed a
462 regression between production, dummies (categorical variables taking the value 0 or 1) for
463 seasonal fluctuations, linear and quadratic time trends, and a dummy for red tide event. The

464 same approach was used to address the effect of the red tide on price change and value of
465 production.

466 Barbier (1998) and Hanley and Barbier (2009) showed a limitation of the dose response
467 approach in that it ignores modification in the economic behavior of the individual affected
468 by the environmental change. Hence, a better way to operationalize a damage function in
469 the context of aquaculture is by the implementation of a production function approach,
470 where the physical impact is one of the inputs in the function along with capital and labour.
471 The marginal value of this impact is a measure of the physical change on the productivity of
472 any marketed output (a monetary value can be obtained by multiplying this change by the
473 market price). A dynamic version (i.e. considering time) of a production function approach
474 was implemented in a bio-economic model by Fresard et al. (2006) to simulate the
475 competition for space from an invasive species for the scallop fishery of the Bay of Saint-
476 Brieuc (France), and then to quantify the net benefit of different scenarios simulating
477 invasion control. The advantage of a dynamic approach is to take account of the effect on
478 the stocks' reproduction rate that is ignored by the static approach. More commonly,
479 studies implementing a static production function have been applied to agriculture to
480 explore the marginal change in crop production of water recharge (Acharya and Barbier,
481 2000), but also to aquaculture to explore those inputs that affect productivity (amongst
482 others stock density, fodder and fertilizer) (Asamoah et al., 2012). Static production
483 functions have been used several times to explore the role of environment on fishery
484 productivity by modelling the habitat-fishery linkage, as proposed by Lynne et al (1987), Ellis
485 and Fisher (1987), Freeman (1991), Barbier (2000), Sathirathai and Barbier (2001) and
486 Barbier et al. (2002). Conversely, there are no studies to our knowledge applying a
487 production function approach to shellfish aquaculture affected by HABs.

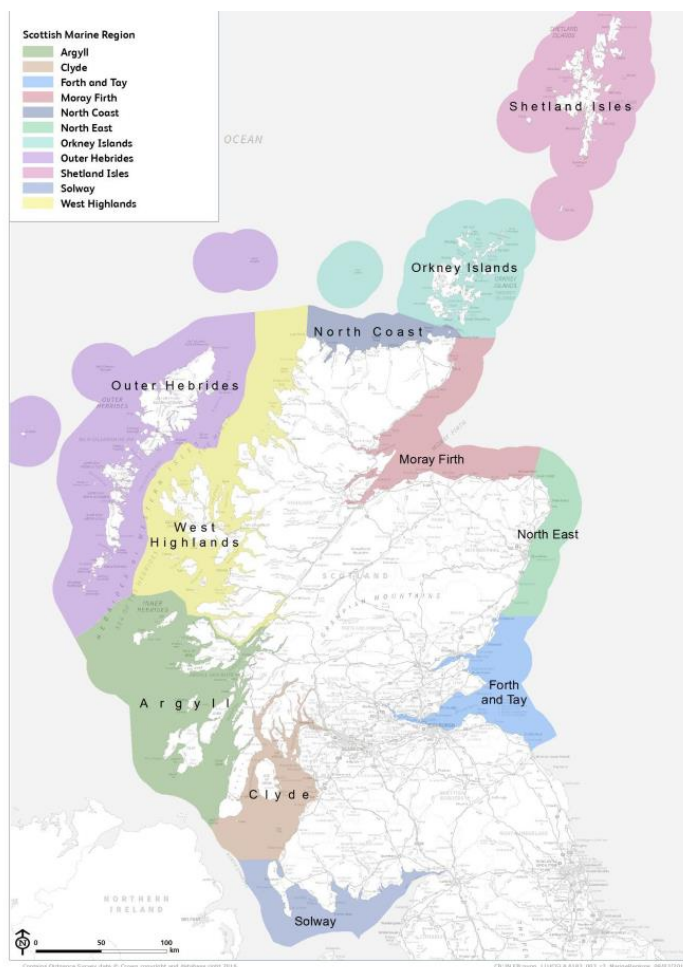
488 This study proposes a static production function approach applied to aquaculture shellfish
489 production in the four most productive Scottish shellfish harvesting regions (Shetland
490 Islands, West Highlands, Outer Hebrides and Clyde) over the period 2009-2018, to estimate
491 the impact of HABs and related biotoxins on shellfish industry productivity. The production
492 function is preceded by a multivariate time series statistical approach (vector
493 autoregression-VAR) to forecast the impact of biological and climatic variables on the
494 production of biotoxins. Although the two models are independent, the VAR can be used to
495 instrument biotoxins in the production function to forecast the expected impacts on
496 shellfish production. Before moving to the details of the statistical approach and results, a
497 brief description of the Scottish shellfish industry, along with the effects of climatic,
498 environmental and biological factors on shellfish production is reported.

499

500 *1.2 Shellfish production in West Scotland*

501 Total shellfish production in West Scotland has been quite stable during the period 2009-
502 2018 at an average of nearly 7,200 tonnes per year. The lowest production occurred in 2013
503 (6,935 tonnes), and the highest in 2016 (10,586). Over the same period, average price was
504 £1,270/tonne (in real 2015 GBP). This production is carried out in nearly 160 active sites
505 employing globally 330 workers. The region that exhibits the highest production is the
506 Shetland Islands with 4,825 tonnes, followed by West Highlands (850 tonnes), Clyde (843
507 tonnes) and Outer Hebrides (678 tonnes). Shetland Islands is the region characterised by the
508 highest capital-intensive production with 75 sites employing in total 112 staff.

509 Figure 1 provides a map of all the marine Scottish regions, but not the geolocation of the
 510 samples². Our study refers only to the four highest shellfish producing regions, the Shetland
 511 Islands and the Western marine regions (Outer Hebrides, West Highlands, Argyll & Clyde).
 512



513

514 Figure 1: Map of the marine Scottish regions. Source: LUC, 2016

515 Within each region, biotoxins and HAB concentrations are evaluated (typically weekly) at a
 516 number of representative monitoring points (RMPs). Shellfish farms operate until biotoxin

² Marine Scotland reports the number of farms sampled in the annual publication “Scottish Shellfish production Survey”, available at the following web site: <https://www.gov.scot/collections/scottish-fish-farm-production-surveys/>. In 2019, 129 businesses were sampled, distributed as follows: 44 in the West Highlands, 5 in the Orkney Island, 23 in the Shetland Islands, 43 in the Clyde, and 14 in the Outer Hebrides. Consulted on 21st August 2020

517 concentrations at the relevant RMP exceed regulatory threshold (see Appendix Table A0)
518 and all the farms associated with this RMP are then closed to harvesting. At concentrations
519 close to the threshold, a risk management matrix that utilises phytoplankton and biotoxin
520 data from the current and previous four weeks is used to determine the appropriate
521 harvesting action. Mussels eventually depurate toxins naturally and reach health and safety
522 conditions required by the market. However, because much of Scottish shellfish production
523 fulfils commercial contracts to supply a particular quantity of product at a certain time, it is
524 likely that this product will go out of phase with market demand and remain unsold.

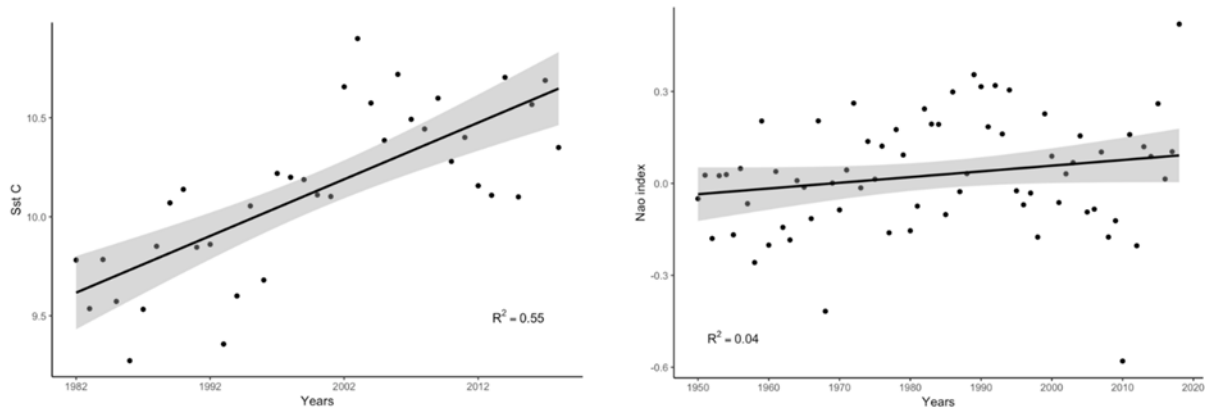
525

526 *1.3 Recent trends in climatic and environmental index, harmful algae and biotoxins*

527 In many locations, the frequency and intensity of HAB events vary according to species and
528 biotoxin both geographically and seasonally. Details on the spatial distribution of HABs in
529 the Scottish marine regions are reported in Food Standards Scotland annual reports (e.g.
530 Stubbs et al. 2015). Inter-annual variability is potentially related to climatological drivers
531 (Belgrano et al., 1999; Moita et al., 2016; Wells et al. 2019). Nevertheless, higher occurrence
532 of blooms during summer seasons suggests that increased sea surface temperature, light
533 intensity and duration, and favourable wind conditions can enhance the proliferation of
534 HABs (Chapelle et al., 2015; Cusack et al., 2016; Fraga et al., 1988; Peperzak, 2003; Whyte et
535 al., 2014). Because of the complex fjordic nature of its coastline, spatial and temporal
536 variability is a characteristic of Scottish waters with different HAB species blooming
537 independently of each other (Davidson et al., 2016) as documented for *Dinophysis* (Swan et
538 al., 2018), *Alexandrium* (Bresnan et al., 2008) and *Pseudo-nitzschia* (Roland-Pilgrim et al.,
539 2019).

540 While Scottish HAB events are thought to be primarily influenced by environmental rather
541 than anthropogenic factors (Gowen et al., 2012), the nature of this interaction, that differs
542 for different species, remains a topic of active research (Bresnan et al., 2020). The North
543 Atlantic Oscillation (NAO) varies between years (Fig. 2 right) without showing any trend.
544 Advective transport of cells by oceanographic and wind driven currents, that are influenced
545 by NAO, has been documented by a number of studies (e.g. Davidson et al., 2009, Whyte et
546 al., 2014), but the mechanism of bloom initiation is less clear. Elevated NAO is related to the
547 westerly winds that may advect harmful blooms developed offshore to the Scottish coastal
548 aquaculture sites (Fehling et al., 2012, Aleynik et al., 2016, Whyte et al., 2014). Ocean
549 warming (Fig. 2 left) has been associated with accelerating the growth rate and widening
550 the distribution of toxic species such as *Dinophysis acuminata* and *Alexandrium fundyense*
551 (Gobler et al., 2017; Wells et al., 2019) in Scottish waters, however other authors have been
552 unable to verify such model predictions (Dees et al., 2017; Hinder et al., 2012).

553 The abundance of the diatom *Pseudo-nitzschia spp.* and its biotoxin product, domoic acid,
554 were noted to increase with temperature by Rowland-Pilgrim et al. (2019), but also
555 exhibiting high inter-annual variability. This genera and other diatoms have showed a
556 positive relationship with the increasing trend of SST in the N.E. Atlantic and North sea using
557 a 50 year time series of Continuous Plankton Recorder data (Hinder et al., 2012). In contrast
558 the same authors showed a negative relationship between most dinoflagellates surveyed
559 and SST.



560

561 Figure 2: Left, SST yearly average for the time series 1982-2018, (PODAAC) website, carried
 562 out by NOAA. Right, Yearly NAO index 1950-2018, NOAA.

563

564

565 2. Data and Methods

566 2.1 Data

567 Our analysis is based on a panel built on the statistics reported by the “Scottish Shellfish
 568 Production Survey” (available years 2009-2018) (see: <https://www.gov.scot/publications/>)³.

569 A panel is a database characterising different individuals or units observed at several points
 570 in time. For each region (unit) of Western Scotland where shellfish are produced (Clyde,
 571 West Highland, Outer Hebrides and the Shetland Islands), the panel is made of 10 (annual)
 572 observations (from 2009 to 2018).

573

574

575

³ Digital data on shellfish production are provided by Marine Scotland. Data at:
<https://data.marine.gov.scot/dataset/scottish-shellfish-farm-production-survey-data>.

576 Regional data used in the analysis are annual shellfish production (expressed in tonne - 96%
577 are mussels), number of employees per region (labour), number of active production sites
578 per region (a proxy for capital), and biological information on harmful algae and biotoxin
579 concentration. Variables common to the four regions are climatological drivers such as sea
580 surface temperature (SST) and the North Atlantic Oscillation (NAO). SST data were obtained
581 from the Physical Oceanography Distributed Active Archive Center (PODAAC) website,
582 reporting daily satellite (AVHRR) derived product with a spatial resolution of 0.25 degrees.
583 The NAO index (interval -1 to 1) was obtained from daily values, calculated by the standard
584 deviation of the monthly NAO index of the time series 1950-2000, by the NOAA National
585 Weather Service Climate Prediction Centre.

586 Biological data are collected by weekly survey from April to October and fortnightly in
587 winter from ~40 phytoplankton and ~80 biotoxin RMPs. These consist of the density of the
588 different relevant HAB species/genera and their associated shellfish biotoxins. To address
589 variability in sampling frequency in different locations these are averaged annually.
590 Phytoplankton collection involves a 10-metre "Lund tube" or occasionally the use of a
591 bucket at shallow water sites. The abundance of harmful phytoplankton cells is enumerated
592 by light microscopy. Biotoxin levels in shellfish tissue are quantified analytically using liquid
593 chromatography with tandem mass spectrometry (LC-MS/MS) and High Performance Liquid
594 Chromatography (HPLC). These techniques were used from 2011, while in the previous
595 years biological assays were employed. Common mussels represent 87% of the total
596 shellfish samples and 62.3% of the samples within which biotoxin concentrations are above
597 the safety threshold for consumption. This shellfish group was therefore chosen for our
598 study since it is the dominant shellfish product in Scotland.

599 HAB abundance and biotoxin concentrations are characterised with respect to the
600 regulatory threshold (Table A0 in Appendix). Abundance values taken from phytoplankton
601 genera and concentrations of harmful shellfish biotoxins are classified in terms of the
602 fraction of measurements (interval 0-1) above the regulatory safety threshold. For
603 phytoplankton, the regulatory threshold is determined by the United Kingdom National
604 Reference Laboratory for marine biotoxins (UKNRL). For biotoxins, this threshold is provided
605 by the regulation (EC) No 853/2004 of the European parliament (European Union, 2004).

606

607 *2.2 Methods*

608 2.2.1 The vector autoregression model

609 It is possible to forecast the variation in shellfish production if we have a dynamic model
610 describing the expected concentration of biotoxins and HABs (see Davidson et al., 2016 and
611 references therein). A simple approach to forecast biotoxins is a multivariate time series
612 model in which each variable is regressed versus lagged regressors, including the dependent
613 variable (vector autoregression - VAR). This is a stochastic process capturing the linear
614 interdependencies among time series. In a VAR, each variable has an equation explaining its
615 evolution based on its own lagged values, the lagged values of the other model variables,
616 and an error term (Verbeek, 2017). The VAR model proposed here does not mimic the
617 physical relations between biotoxins and climatic variables, but describes how variables
618 affect each other inter-temporally. The optimal order of the lagged variable, usually selected
619 by BIC and AIC criterion (Verbeek, 2017), is indicated by the letter “p”. A VAR is usually
620 explained by the following matrix expression:

$$621 \quad Y_t = c + A_1 Y(t-1) + A_2 Y(t-2) + \dots + A_p Y(t-p) + e_t \quad \text{Eq.1}$$

622 where Y_t is the vector of dependent variables at the current time t , the observation $Y(t-i)$ up
 623 to the order p is the i -th lag of vector Y , c is a vector of constants (intercepts), A_1, A_2, \dots, A_p
 624 are time-invariant matrices of coefficients at lag 1, 2, ..., p , and e_t is a k -vector of error terms
 625 with zero mean and no serial correlation. In a VAR, all the variables must be stationary, i.e.
 626 mean variance, autocorrelation, etc. are all constant over time. Stationarity of vector Y_t is
 627 verified for our data set according to the augmented Dickey-Fuller test (Dickey and Fuller,
 628 1979) as reported in the Appendix Table A1.

629

630 2.2.2 The Cobb-Douglas production function

631 A production function is a mathematical relation that defines the highest level of production
 632 achievable as a function of a range of inputs, such as labour and capital (Cobb and Douglas,
 633 1928). Alternative models including environmental variables as input factors are common
 634 for the agriculture sector (Umar et al., 2017). Eq.2 depicts the relationships between
 635 shellfish production and several covariates, including climatic variables (SST and NAO) and
 636 ecological information (the concentration of harmful algae and biotoxins).

$$637 \quad Production_{jt} = A_j * K_{jt}^{\beta_1} * L_{jt}^{\beta_2} * e^{\beta_3 SST_t + \beta_4 NAO_t + \beta_5 HAB_{jt} + \beta_6 BTX_{jt}} * \epsilon_{jt} \quad \text{Eq.2}$$

638 where *Production* is shellfish production (allocated to market) in tonnes, K is capital, proxied
 639 by the number of active producing sites, L is labour, the total number of employees; SST and
 640 NAO are the sea surface temperature in degrees Celsius, and the North Atlantic climatic
 641 index (in the range -1 to 1), respectively; j is an index for the j^{th} region (unit) of production at
 642 time t . HAB is the vector of harmful algal bloom variables, and BTX is a vector of biotoxin

643 variables produced by the *HAB*. Both are expressed in frequency, i.e. the fraction (interval 0-
 644 1) of algal cell and biotoxin concentration above a harmful threshold that impedes the
 645 commercialisation of shellfish (reported in Table A0 of the Appendix). The symbol e is the
 646 mathematical constant (Euler's number) approximately equal to 2.71828, the base of the
 647 natural logarithm⁴. Finally, A is the constant that refers to technology or management
 648 producing strategies and ε is the error term. Hence, A is the amount of production for a unit
 649 value of K and L , while the effect of *SST*, *NAO*, *HAB* and *BTX* is null. The beta coefficients of
 650 Eq.2 measure the impact of each covariate on shellfish production. To estimate Eq.2, all
 651 variables with the exclusion of *SST*, *NAO*, *HAB* and *BTX*, are transformed in natural log. Eq. 2
 652 then becomes:

$$653 \ln Production_{jt} = \ln A_j + \beta_1 \ln K_{jt} + \beta_2 \ln L_{jt} + \beta_3 SST_{jt} + \beta_4 NAO_{jt} + \beta_5 HAB_{jt} +$$

$$654 \beta_6 BTX_{jt} + \ln \varepsilon_{jt} \quad \text{Eq.3}$$

655 Having operated this transformation, the beta coefficients of K and L (β_1 and β_2 ,
 656 respectively) can be interpreted as elasticities, i.e. the percentage variation in production
 657 triggered by a percentage change in capital and labour. As *HAB* and *BTX* are measured as
 658 frequency (0 to 1), the interpretation of their respective beta coefficients is that 1% change
 659 in *HAB* and *BTX* causes a relative change in production nearly equivalent to the beta
 660 coefficient. The constant $\ln A$ refers to the natural log of production under unitary labour
 661 and capital. The *HAB* and *BTX* beta coefficients can then be seen as the marginal change of
 662 productivity under undesirable conditions.

⁴ It is necessary to introduce in the Cobb-Douglas the exponential of *SST*, *NAO*, *HAB* and *BTX* because under this formulation there is no adverse effect on production of shellfish if these variables are equal to zero. Conversely, a multiplicative formulation would imply zero production under a null value of one of these environmental variables (the latter formulation is obviously incorrect).

663 In Eq.3 climatic variables and HAB have a mediating, but not direct, effect on shellfish
 664 production through their influence on BTX (see Supplementary Material 1 for more
 665 information). Thus BTX are endogenous variables (i.e. that are influenced by other variables,
 666 and then generated within the model), while SST, NAO and HAB are exogenous variables
 667 (whose value is determined outside the model). To treat this issue, we solved Eq.3 by a
 668 regression with instrumental variables, where the instruments are the exogenous variables
 669 SST, NAO and HAB correlated to the instrumented or endogenous variable (BTX), but
 670 uncorrelated with the error terms of Eq.3 and unaffected by the remaining variables.

671 A panel data regression with instrumental variables is executed in two stages: the first is a
 672 regression between the endogenous variable and exogenous regressors to test for the
 673 goodness of the instrument (weak correlations can lead to misleading estimates for
 674 parameters and standard errors of Eq.3). The second regression is the analysis of the panel
 675 where the instrumented variable is replaced by the predicted values of the first stage
 676 regression. For details, see Verbeek (2017). To take account of this endogeneity, Eq.3 is
 677 therefore simplified as follows:

$$678 \ln Production_{jt} = \ln A_j + \beta_1 \ln K_{jt} + \beta_2 \ln L_{jt} + \beta_6 BTX_{jt} + \ln \varepsilon_{jt} \quad \text{Eq.4}$$

679 where labour and capital are exogenous and BTX is instrumented by NAO, SST and HABs.

680 Eq.4 is estimated using both fixed and random effect estimator to depict the impacts of BTX
 681 on shellfish production. A fixed effect estimator provides meaningful results explaining the
 682 differences between units (the productive regions). Such estimator assists in controlling for
 683 unobserved heterogeneity when this heterogeneity is constant over time and correlated
 684 with the independent variables. This heterogeneity is usually removed from the data by
 685 regressing the mean-corrected variables (i.e. the difference of each observation from the

686 variable's mean). We can assume that in the production function time invariant omitted
687 variables can be management practices (different strategies that are adopted in production,
688 for example to mitigate the impacts of algal blooms that are not observed and captured by
689 the model) and the site characteristics of the farm such as the particular habitat or
690 substrate. Under the fixed effect estimator, we assume that each unit or region has its own
691 specific characteristics (modelled by a unique intercept) rather than being considered a
692 random draw from the same population. These unit-specific means ($\ln A_j$ in Eq.4) take
693 account of the regional variability in the productivity of each region. The two stage least
694 squares (2SLS) estimator with regional dummy variables is used to capture the productivity
695 of each unit. Conversely, the random effect model does not estimate any fixed time
696 invariant intercept for each unit, but assumes that the regions are drawn from a larger
697 (random) sample. This model assumes also that unobserved heterogeneity is not correlated
698 with the independent variables. The random effect coefficients are estimated by the two
699 stages generalised least squares estimator (G2LS). Statistical analysis was carried out in
700 STATA version 16.0.

701

702

703 **3. Results**

704 *3.1 Descriptive statistics*

705 Table 1A, 1B, 1C summarise the average values for all the covariates for each unit of the
706 panel. A large difference is discernible between the Shetland Islands and the other regions.
707 In particular, the production in Shetland is at least twice as high as in all other regions and is

708 achieved by employing the lowest number of workers per site (Table 1A). It is therefore
709 evident that Shetland has the lowest labour intensity measured as labour to capital ratio
710 (1.48 labour units per active site compared to 2 to 3 labour units per site of the other
711 regions) (Table 1A). As regards algal concentration, only the genera *Alexandrium*, *Dinophysis*
712 and *Pseudo-nitzschia* overcome significantly the harmful threshold (see Table 1B), while
713 amongst the biotoxins, those causing DSP most frequently exceed regulatory threshold
714 (Table 1C).

715

716

Table 1A, 1B, 1C here

717 Table 2 reports the pairwise correlation between all the variables. Significant correlations
718 are denoted with an asterisk. Production is positively related to capital and labour as
719 expected, but capital and labour are highly correlated suggesting potential collinearity.
720 Positive changes in the climatic index NAO, associated with offshore-onshore advection of
721 cells, is expected to increase the concentrations of DSP biotoxins. SST has an inverse impact
722 on PSP, but does not affect any other biological variables. Finally, *Pseudo-nitzschia* is
723 negatively related to DSP, PSP and AZP, consistent with the observation that environmental
724 conditions that facilitate the proliferation of diatoms do not favour the growth of
725 dinoflagellates.

726

727

Table 2 here

728

729 *3.2 Prediction of DSP biotoxins: the VAR model*

730 Table 3 shows the statistical relations between climatic index, HAB and BTX variables (as
731 provisionally depicted by the pairwise correlation shown in Table 2) to forecast
732 concentration of biotoxins at time t having information of all covariates at time $t-1$ (at
733 higher lags, no significant result is found). Only the regression presenting DSP as dependent
734 variable is reported, because of the highest explained variance (R squared 67%) and the
735 importance of DSP in affecting production in the Cobb-Douglas model presented in section
736 3.3.

737

738 **Table 3 here**

739

740 It is evident from the coefficients reported in Table 3 that lagged values of DSP do not
741 explain the current value of DSP (i.e. blooms in a particular year are independent of those in
742 previous years). As expected, *Dinophysis spp.*, that is the main causative dinoflagellates of
743 toxins generating DSP in Scotland (Swan et al., 2018), is positively contributing to DSP.
744 Conversely, *P. lima*, that can also generate DSP toxins, is negatively related. This opposite
745 response is not however a surprise: *Dinophysis spp.* and *P. lima* have different life cycles, so
746 there is no expectation that both will bloom at the same time. Finally, the NAO index is
747 highly correlated at lag 1 with DSP. In other words, we can say that data lagged 1 year for
748 NAO are able to forecast the current (present) DSP. This relationship is positive; this means
749 that a higher NAO index contributes to increase the concentration of DSP biotoxins. The
750 result is not easily interpretable from an ecologically perspective, especially for the low
751 temporal resolution of the database and because this regression does not mimic any
752 structural behaviour in DSP formation, i.e. it is not clear ecologically how NAO the previous

753 year influences DSP in the current year. However, the predictive capacity of a VAR is quite
754 good and can contribute to forecast DSP, in the absence of a complex physical model
755 working at higher spatial and temporal resolution. Although this result is *per se* meaningful,
756 it can also be used with the regression model described in section 3.3 to predict the
757 expected damage on shellfish production and facilitate mitigating losses in production with
758 an ample temporal margin. To achieve this, the predicted value of DSP from the VAR can be
759 multiplied by the marginal change in production caused by DSP (section 3.3). An estimate of
760 average damage caused by the value of DSP in the period 2009-2018 is reported in the
761 discussion.

762

763 *3.3 The econometric model*

764 Supplementary Material 1 reports several tests justifying the choice of a panel data
765 regression with instrumental variables to estimate Eq.4. Table 4a reports the coefficients
766 estimated by the random effect estimator, while Table 5a reports results from the fixed
767 effect estimator, the latter to take account of the potential differences in productivity
768 between regions, as evidenced by Table 1. Estimates are accompanied by clustered robust
769 standard errors to correct for the presence of heteroscedasticity (Supplementary Material 2
770 plots residuals versus fitted values showing non-homogeneous dispersion of residuals).

771 Table 4b and Table 5b report the first stage regression under random and fixed effect
772 estimators respectively, showing the goodness of the instrumental variables in predicting
773 DSP. All covariates included in the models proposed are statistically significant.

774 The random effect estimator shows that labour is negatively related to production, a result
 775 that is economically counterintuitive. Conversely, as expected, the effect of capital on
 776 production is positive and elastic, showing that 1% increase in capital contributes to
 777 increase production by 1.88%. The marginal effect of DSP on production is close to 1,
 778 meaning that 1% increase in DSP causes nearly 1% reduction in production.

779

780

Table 4a here (random effect)

781

Table 4b here (first stage random effect)

782

783 Under the fixed effect model, labour does not show any statistically significant effect on
 784 productivity. This can be interpreted as the possibility that farming has reached the highest
 785 level of productivity given the capital employed (according to the law of marginal
 786 diminishing return), i.e. one unit more of labour does not contribute to an increase in
 787 productivity⁵. Conversely, the impact of capital is positive and close to the unit elasticity.
 788 The impact of DSP is -0.66, i.e. 1% increase in DSP causes a reduction of 0.66% in shellfish
 789 production. The constant term shows the productivity for the Clyde region. The coefficient
 790 for the Outer Hebrides, West Highlands and Shetland Islands shows the additional
 791 productivity above that of the Clyde region⁶. Table 5a coefficients for the regions Outer

⁵ Removing from the panel data regarding the Shetlands Island, the region characterized by the highest intensity of capital, both labour and capital become insignificant. This shows that results from labour is in part due to the limited variability of the database, while that from capital is influenced by the higher productivity of Shetland's farms.

⁶ By adding the constant (coefficient for the Clyde) to the specific coefficient of the region of interest, it is possible to obtain the fixed term effect for any region. The coefficient of the Outer Hebrides is therefore 4.265 (standard error of 1.635); that of West Highlands is 4.226 (standard error 1.973), while Shetland is 5.068 (standard error 2.244), confirming the highest productivity in this region as expected from descriptive statistics in Table 1.

792 Hebrides and West Highlands do not show any significant incremental productivity
793 compared to the Clyde, while Shetland Islands show a significant higher productivity as
794 expected from Table 1. The null hypothesis on the equality of the coefficients between the
795 Clyde and Outer Hebrides ($\chi^2(1)=0.16$, $\text{prob}>\chi^2=0.689$) and Clyde and West Highlands
796 ($\chi^2(1)=0.54$, $\text{prob}>\chi^2=0.462$) cannot be rejected, while a significant difference exists
797 between Clyde and the Shetlands ($\chi^2(1)=42.91$, $\text{prob}>\chi^2=0.000$), confirming the highest
798 productivity of the second region as expected from descriptive statistics in Table 1.

799

800

Table 5a here (fixed effect)

801

Table 5b here (first stage fixed effect)

802 To estimate the impact of DSP on shellfish production we opted for the coefficients
803 provided by the fixed effect model. This has the advantage of considering difference in
804 productivity among sites (the different regions appears as single independent units) and
805 removing time invariant aspects related to the management of the fisheries. This model
806 also provides a lower marginal impact of DSP on production compared to the random effect
807 model. Finally, the Hausman test (Verbeek, 2017) confirms fixed effect to be the most
808 efficient estimator ($\chi^2(3) = 41.88$, $\text{Prob}>\chi^2 = 0.0000$).

809

810

811 **4. Discussions and conclusions**

812 *4.1 Main findings and implications for shellfish management*

813 We have investigated the extent to which shellfish production in Scotland is influenced by
814 algal toxins proposing two models: a VAR to depict the relation between biological, climatic

815 drivers and biotoxins concentration and a production function to describe the impact of
816 biotoxins on shellfish production. The VAR found a statistically significant relationship
817 between a positive change in some harmful algae, the NAO index and DSP biotoxins. This
818 result is interesting because environmental drivers of *Alexandrium*, *Dinophysis* and *Pseudo-*
819 *nitzschia* blooms (Smayda, 2004, Davidson et al., 2011, Bresnan et al., 2020) have not been
820 clearly explained (Dees et al., 2017, Bresnan et al., 2020). Future development of the VAR at
821 higher resolution may capture the ecology of DSP formation. For example, findings of this
822 model can be further investigated to check if they are consistent with the hypothesis that
823 Scottish DSP events are related to changes in atmospheric pressure and hence that
824 *Dinophysis* blooms develop offshore and are advected to the coast (Whyte et al., 2014;
825 Aleynik et al., 2016, Paterson et al., 2017).

826 The production function showed that DSP toxicity on production follow a non-linear pattern,
827 i.e. shellfish production changes at decreasing rate (speed of change) at higher
828 concentration of DSP biotoxins. In particular, we found that a 1% change in DSP biotoxins
829 above the harmful threshold defined for regulatory purposes causes a reduction in
830 production of 0.66%. Considering that the average yearly proportion of DSP biotoxin
831 concentration above the threshold in the last 10 years has been 24% (see Table 1), these
832 toxins are expected to cause a yearly average reduction of nearly 15% in production (95%
833 confidence interval -20% to -10%). This change is equivalent to a loss of 1,080 ton of
834 shellfish per year (95% confidence interval -1,490 ton to -670 ton). At the average price of £
835 1,272 per ton (in 2015 constant GBP), the average annual economic damage (expressed as
836 lost gross revenue) caused by DSP is equivalent to £ 1.37m (95% confidence interval £-1.9m
837 to £-0.85m) over a turnover of approximately £10.1m.

838 Other authors (Hoagland et al. 2002) used as an indicator of economic impact the lost
839 revenue. Under the assumption that harvested production cannot be easily commercialised
840 after the ban, as it happens for the Scottish shellfish, lost revenue becomes a good indicator
841 of the real benefits lost (producer surplus).

842 Commonalities with case studies reported in the literature are difficult to find because of
843 the paucity of research applied to shellfish production and inconsistency in the
844 methodologies used to assess impacts. HAB damage to Korean shellfish aquaculture over
845 the past 3 decades amounted to US\$ 4m per year and peaked in 1995 to US\$ 60m, almost a
846 10% loss of all cultured shellfish produced that year (Park et al., 2013). In percentage terms,
847 this figure is similar to our findings. In another study carried out in Spain (Rodriguez et al.,
848 2011), the economic impact of DSP biotoxins on mussel production was not yet clearly
849 established. A difficulty in forecasting the economic loss caused by DSP in the Spanish
850 market is related to the possibility to sell part of the produce after shellfish deplete. In
851 fact, while significant biotoxin events may lead to a reduced harvest, the Spanish case
852 demonstrates that at least part of the production that cannot be harvested during the
853 closure of the fishery can be marketed after the prohibition period (Rodriguez et al., 2011).
854 This is not always possible in Scotland, although mitigating measures do exist such as
855 shifting production to adjacent sites, if possible. Some cooperatives (for example the
856 Scottish Shellfish Marketing Group) help farmers in different geographical areas to work
857 together to switch production to fjords that have not been impacted by HABs.

858 The mitigating strategies mentioned above can be adopted by firms to adapt capital and
859 labour to maximise production in light of environmental conditions. The Cobb-Douglas
860 approach, as it considers capital as input factor, is able to include more explicitly farmers

861 behavioural as captured by the varying number of sites of production in order to anticipate
862 production during a HAB event. This cannot be modelled in the dose response model (Jin et
863 al., 2008; Rodriguez et al., 2011).

864 In terms of management implications for the Scottish shellfish industry, results from the
865 production function show that shellfish production is more efficient in the Shetland Islands,
866 characterised by higher productivity compared to the regions of the west coast. These
867 results offer insight into regional differences in operation and the environmental
868 characteristics of the sites. Although not an object of this study, we can say that studying
869 the productivity in the different regions would allow more informed management to
870 support the sustainable development of the shellfish industry. In the West Highlands,
871 characterized by a lower productivity, the impact on production is marginally more
872 damaging than in the Shetlands, suggesting managers may be able to put in place strategies
873 to minimize the impacts of harmful algae, from shifting production sites to rearranging
874 contractual agreements with wholesalers and retailers.

875

876 *4.2 Limits of the model*

877 There are some limits to our econometric model that future research should address. The
878 first one is the lack of suitable variables to explain capital and labour in the West Highland
879 farms that both show a limited variability in the period 2009-2018. In addition, the capital of
880 the fishery shows a high correlation with labour (Table 1), and may be the cause of the non-
881 significance of the variable labour in the regression. We found that the ratio of workers to
882 active sites is approximately constant over time with a value of \sim two. A constant labour to
883 capital ratio is typical of a production function characterised by a relation of

884 complementarity between capital and labour (i.e. production is achieved using the same
885 units of capital and labour), while the Cobb-Douglas production function is characterised by
886 capturing the substitutability between factors (production can be achieved trading-offs
887 capital against labour or vice versa). Therefore, further development of the model requires a
888 different proxy for the capital: this can be the area that each farm is dedicating to
889 production, the number of producing longlines, or the ratio between longlines and area.
890 These data were not available to us for this study, but could potentially be collected by
891 questionnaire survey at farm level.

892 While the HAB and biotoxin time series available to us are possibly unique in length, both in
893 temporal and spatial resolution, our analysis is also limited by the lower resolution of, for
894 example, production data, which is surveyed only annually. The regression model proposed
895 simulates the impacts of HAB and biotoxins concentration over the regulatory safety
896 threshold and on averaged yearly production. Thus, this approach is able to capture the
897 variability of biotoxins which are characterised by medium term blooms lasting for much of
898 a season as can be the case for *Dinophysis spp*, which occur anywhere on Scottish coastal
899 waters without a clear and evident regional pattern (Smayda, 2004, Coates et al., 2018,
900 Bresnan et al., 2020,)) and therefore are likely to have a non-seasonal impact on shellfish
901 harvesting. Conversely, short term blooms of PSP toxins from the genus *Alexandrium*, which
902 are regularly detected in mussels during the summer months (Bresnan et al., 2008), are not
903 captured by our model because of its limited temporal resolution (1 year). Hence, we are
904 unable to capture factors such as seasonality of HAB and its impact on shellfish productivity.
905 Ideally, future studies would include higher temporal resolution farm data (possibly by
906 capturing seasonal production at farm scale by questionnaire survey of all farms). This
907 would have the advantage of distinguishing whether each site differs from others and if

908 seasonal HAB events have an impact on production. Availability of data at a higher temporal
909 resolution would also facilitate the implementation of a more general function such as the
910 translog that is able to capture non-linear (quadratic) and cross-effects among the
911 regressors (Umar et al., 2017), and may reveal more detailed temporal or spatial impacts of
912 HABs on production.

913 A final consideration is how to get the best from the results of this model. These could be
914 maximised in future research by a model capturing the dynamics of the shellfish market, to
915 provide insights on the equilibrium between demand and supply and to address HABs
916 impacts not only on the shellfish harvest, but also on prices to allow estimation of welfare
917 changes from the side of consumers.

918

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924

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TABLES

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1138 **Table 1A: Descriptive statistics (mean, standard deviation in parenthesis) for the**
 1139 **productive/economic variables of Scottish shellfish industry in each region for the period**
 1140 **2009 to 2018. Unit of measure is ton for shellfish production, number (#) of active**
 1141 **producing sites for capital, number of employees for labour, and number of employees**
 1142 **per site as a measure of capital intensity.**

Region	Production (t)	Active sites (#)	Labour (#)	Labour/sites (#)
Clyde	842.279 (278.89)	36.712 (5.14)	113.128 (7.86)	3.081 (0.39)
Outer Hebrides	678.670 (262.18)	19.063 (3.00)	32.841 (3.25)	1.723 (0.30)
Shetland	4,825.707 (989.56)	75.334 (16.9)	111.860 (12.18)	1.485 (0.49)
West Highland	850.315 (253.56)	28.336 (1.79)	74.224 (12.55)	2.619 (0.47)

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1149 **Table 1B: Descriptive statistics (mean, standard deviation in parenthesis) for harmful algae**
 1150 **for each region in the period 2009 to 2018. Unit of measure is the interval 0 to 1 (fraction**
 1151 **above the critical damaging threshold as shown in the Table A0 reported in the Appendix).**
 1152 **The Table reports also temperature and NAO index. They are common for all regions.**
 1153 **Temperature is measured in degrees Celsius, NAO index is expressed in the interval -1 to**
 1154 **1.**

Region	<i>Pseudo-nitzschia</i> (0-1)	<i>Alexandrium</i> (0-1)	<i>Dinophysis</i> (0-1)	<i>Prorocentrum</i> (0-1)
Clyde	0.046 (0.028)	0.136 (0.054)	0.162 (0.053)	0.011 (0.005)
Outer Hebrides	0.076 (0.047)	0.183 (0.061)	0.127 (0.079)	0.010 (0.007)
Shetland	0.171 (0.099)	0.189 (0.082)	0.148 (0.058)	0.023 (0.033)
West Highland	0.088 (0.048)	0.170 (0.068)	0.224 (0.063)	0.018 (0.013)
		SST (degrees C)	NAO (1-1)	
All Regions		10.395 (0.222)	0.036 (0.021)	

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1161 **Table 1C: Descriptive statistics (mean, standard deviation in parenthesis) for biotoxins in**
 1162 **each region in the period 2009 to 2018. Unit of measure is interval 0 to 1 (fraction above**
 1163 **the critical damaging threshold as shown in the Table A0 reported in the Appendix).**

Region	ASP (0-1)	AZP (0-1)	DSP (0-1)	PSP (0-1)	YTX (0-1)
Clyde	0.006 (0.010)	0.000 (0.000)	0.254 (0.188)	0.001 (0.001)	0.000 (0.000)
Outer Hebrides	0.006 (0.006)	0.020 (0.042)	0.223 (0.138)	0.002 (0.003)	0.002 (0.004)
Shetland	0.004 (0.005)	0.019 (0.041)	0.239 (0.196)	0.000 (0.000)	0.001 (0.001)
West Highland	0.008 (0.010)	0.015 (0.021)	0.247 (0.193)	0.002 (0.002)	0.002 (0.002)

1164 Legend: Diarrheic Shellfish Poisoning (DSP), Paralytic Shellfish Poisoning (PSP), Amnesic
 1165 Shellfish Poisoning (ASP), Azaspiracids poisoning (AZP), Yessotoxins (YTX)

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Table 2: Pairwise correlation between variables. Significant correlations at alpha level 0.05 are reported with an asterisk

	Production	Sites (capital)	Labour	ASP	DSP	AZP	PSP	<i>Alexandrium</i>	<i>Dinophysis</i>	<i>P. lima</i>	<i>Pseudo-nitzschia</i>	SST	NAO
Production	1												
Sites	0.888*	1											
Labour	0.513*	0.757*	1										
ASP	-0.057	-0.131	-0.021	1									
DSP	-0.121	-0.010	-0.0348	-0.2144	1								
AZP	0.101	0.001	-0.1316	0.0326	-0.2181	1							
PSP	-0.250	-0.306	-0.1551	-0.0383	0.2183	-0.0793	1						
<i>Alexandrium</i>	-0.054	-0.113	-0.1096	-0.1626	0.3691*	0.0871	0.1184	1					
<i>Dinophysis</i>	-0.0806	0.041	0.1003	-0.0496	0.2723	0.0305	0.0482	0.1059	1				
<i>P. lima</i>	0.271	0.276	0.1121	0.1712	-0.0704	0.119	-0.0235	-0.133	0.0981	1			
<i>Pseudo-nitzschia</i>	0.54*	0.377*	0.2238	0.0795	(-)0.3413*	0.3977*	(-)0.3170*	0.0987	-0.127	-0.0441	1		
SST	0.001	0.011	-0.0472	0.1651	0.1695	-0.0944	(-)0.3314*	0.0427	-0.3028	-0.0709	0.0127	1	
NAO	-0.118	-0.031	-0.1069	-0.2176	0.699*	0.0904	0.3396*	0.2809	0.0859	0.1447	-0.2835	0.0271	1

1171 Legend: Diarrhetic Shellfish Poisoning (DSP), Paralytic Shellfish Poisoning (PSP), Amnesic Shellfish Poisoning (ASP), Azaspiracids poisoning (AZP),

1172 Yessotoxins (YTX); Sea Surface Temperature (SST); North Atlantic Oscillation (NAO)

1173 **Table 3: Vector auto regression (VAR) modelling the value of DSP as a function of lagged**
 1174 **values of HABs, biotoxins, NAO and SST**

1175 *Dep. Variable* *R-sq* *chi2* *P>chi2*
 1176 *DSP* *0.677* *81.699* *0.0000*

<i>variables</i>	<i>coefficient</i>	<i>Std err</i>	<i>z</i>	<i>P>z</i>
<i>DSP_L1</i>	0.0054	0.1255	0.04	0.966
<i>Alexandrium_L1</i>	0.2923	0.2635	1.11	0.267
<i>Dinophysis_L1</i>	0.5536	0.2444	2.27	0.023
<i>P. lima_L1</i>	-2.0174	0.8769	-2.30	0.021
<i>Pseudo-nitzschia_L1</i>	-0.0184	0.2584	-0.07	0.943
<i>ASP_L1</i>	-2.1901	2.0313	-1.08	0.281
<i>AZP_L1</i>	0.2077	0.5926	0.35	0.726
<i>PSP_L1</i>	17.2495	9.4221	1.83	0.067
<i>NAO_L1</i>	0.3723	0.0685	5.44	0.000
<i>SST_L1</i>	0.0882	0.0915	0.96	0.335
<i>constant</i>	-0.8021	0.9448	-0.85	0.396

1177 Legend: Diarrheic Shellfish Poisoning (DSP), Paralytic Shellfish Poisoning (PSP), Amnesic
 1178 Shellfish Poisoning (ASP), Azaspiracid poisoning (AZP), Yessotoxins (YTX); Sea Surface
 1179 Temperature (SST); North Atlantic Oscillation (NAO). L1 stands for lag 1.

1180

1181 **Table 4a: Cobb-Douglas production function estimated by random effect estimator with**
 1182 **instrumental variables. Dependent variable: shellfish production. Instrumented variables:**
 1183 **DSP - Instruments: sites, labour, SST, NAO, *Dinophysis*. Analysis carried out using clustered**
 1184 **robust errors.**

<i>variables</i>	coefficient	Robust Std err	t	P>t
<i>Sites</i>	1.889	.108	17.40	0.000
<i>Labour</i>	-.633	.145	-4.37	0.000
<i>DSP</i>	-.914	.318	-2.87	0.004
<i>Constant</i>	3.351	.404	8.29	0.000
<i>N obs</i> 40	Wald chi2(2) 1220.37	R2 within 0.400	R2 between 0.982	R2 overall 0.858
<i>N groups</i> 4	Prob>chi2 0.000			

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1188 **Table 4b: First stage regression estimated by random effect estimator. Dependent**
 1189 **variable: DSP - Instruments: sites, labour, SST, NAO, *Dinophysis*.**

<i>variables</i>	coefficient	Robust Std err	t	P>t
<i>Sites</i>	-.0149	.0523	-0.29	0.776
<i>Labour</i>	.0185	.0513	0.36	0.718
<i>NAO</i>	.437	.0520	8.40	0.000
<i>SST</i>	.195	.0911	2.15	0.032
<i>Dinophysis</i>	.699	.287	2.44	0.015
<i>Const</i>	-1.952	.955	-2.04	0.041
	Wald chi2(5) 117	Prob>chi2 0.000		
	N obs 40	N groups 4		

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1192 **Table 5a: Cobb-Douglas production function estimated by 2SLS estimator with dummy**
 1193 **variables and instrumental variables. Dependent variable: shellfish production.**
 1194 **Instrumented variables: DSP - Instruments: sites, labour, SST, NAO, *Dinophysis*. Clustered**
 1195 **robust errors are shown.**

<i>variables</i>	coefficient	Robust Std err	t	P>t
<i>Sites</i>	.959	.265	3.62	0.000
<i>Labour</i>	-.122	.277	-0.44	0.660
<i>DSP</i>	-.661	.241	-2.74	0.006
<i>Constant_A (Clyde)</i>	4.024	1.924	2.09	0.037
<i>Outer Hebrides</i>	.241	.442	0.54	0.586
<i>West Highlands</i>	.202	.157	1.29	0.197
<i>Shetland Islands</i>		0.187	5.57	0.000
	1.044703			
<i>N obs</i> 40	Wald chi2(6) 877.48	R2 0.9277		
<i>N groups</i> 4	Prob>chi2 0.000			

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1198 **Table 5b: First stage regression for the 2SLS regression with instrumental variable**
 1199 **reported in Table 5a. Dependent variable: DSP. Instruments: sites, SST, NAO, *Dinophysis*,**
 1200 **Clyde, Outer Hebrides, West Highlands, Shetland Islands.**

<i>variables</i>	coefficient	Robust Std err	t	P>t
<i>Sites</i>	-.1352	.127	-1.06	0.298
<i>Labour</i>	.1297	.168	0.77	0.447
<i>NAO</i>	.443	.071	6.27	0.000
<i>SST</i>	.247	.094	2.63	0.013
<i>Dinophysis</i>	1.060	.329	3.22	0.003
<i>Constant (A) Clyde</i>	-2.627	1.410	-1.86	0.072
<i>Outer Hebrides</i>	.0772	.226	0.34	0.735
<i>West Highlands</i>	-.052	.077	-0.69	0.498
<i>Shetland Islands</i>	.098	.136	0.72	0.478
<i>N obs</i>	F(8,31)	R2		
40	18.74	0.621		
<i>N groups</i>	Prob>F			
4	0.000			

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APPENDIX

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1208 **Table A0: harmful threshold concentration for harmful algae and biotoxins**

Toxin	Type of toxin	Syn-drome	Species	Group	Thresho ld cells/ litre	Biotoxin
Saxitoxin	Neurotoxin	PSP	<i>Alexandrium</i> sp	Dino- flagellate	40	>800 µg STX eq. / kg
Okadaic acid and derivatives	Gastro- intestinal	DSP	<i>Dinophysis</i> sp	Dino- flagellate	100	>160µg OA eq. / kg
			<i>Prorocentrum lima</i>	Dino- flagellate		
Domoic acid	Neurotoxin	ASP	<i>Pseudo-nitzschia sp.</i>	Diatom	50 000	>20 mg DA/kg
Yessotoxin (YTX)			<i>Prorocentrum reticulatum,</i>	Dino- flagellate	100	>3.75mg YTX eq./kg
Azaspiracid (AZA)	Gastro- intestinal	AZP	<i>Azadinium</i> sp	Dino- flagellate		>160ug AZA eq./kg

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1211 **Table A1: Augmented Dickey-Fuller test (1979) tests the stationarity of the variables of the**
 1212 **panel. Null Hypothesis: variable is not stationary.**

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Variable	ADF Z test statistics
Production	-2.131(0)* drift
Active sites	-2.51(1)* drift
Labour	-8.53(0)** trend
SST	-3.81(0)* drift
NAO	-5.28(0)** trend
ASP	-3.009(0)** drift
AZP	-4.55(1)** trend
DSP	-1.60(0) #drift
PSP	-3.005(0)** drift
YTP	-1.69(0)# drift
<i>Alexandrium</i> spp	-2.384(0)* drift
<i>Dinophysis</i> spp	-2.884(0)* drift
<i>Prorocentrum</i> spp	-2.041(0)* drift
<i>Pseudo-nitzschia</i> spp	-2.74(1)* drift
In bracket it is reported the optimal lag; Drift= stationarity around a constant mean Trend=stationarity around a trend # significant at 0.10; * significant at 0.05; ** significant at 0.01	

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HARMFUL ALGAE AUTHOR DECLARATION

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