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Assessing Fuzzy Cognitive Mapping as a participatory and interdisciplinary approach to explore marine microfiber pollution

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ABSTRACT

Fuzzy Cognitive Mapping (FCM) is a participatory modelling tool used to explore complex systems by facilitating interdisciplinary cooperation and integrating a variety of knowledge systems. Here FCM was used to explore marine microfiber pollution. Through individual interviews with representatives from the research, industry, water and environmental sectors, five stakeholder FCMs were developed and used to produce an aggregated community FCM in a stakeholder workshop. Stakeholder FCMs and the revised community FCM were used to compute how the modelled system reacted to changes under two scenarios developed during the stakeholder workshop; (i) Green Shift and (ii) increased textile consumption and production. Significant differences were observed in scenario results from the stakeholder-based models and the community-based model. For societal challenges characterized by unknowns around the problem and potential solutions, inclusion of a variety of knowledge systems through FCM and deliberation processes contribute to a more holistic picture of the system and its uncertainties.

1. Introduction

Microplastic fibers are secondary microplastics (≤5 mm) released from synthetic textiles that can make up a considerable part of microplastics in the marine environment (Browne et al., 2011; Hernandez et al., 2017; Laitala et al., 2018; Napper and Thompson, 2016; Salvador Cesa et al., 2017). Although the term microfiber is often used exclusively to describe fibers from synthetic textiles (Mishra et al., 2019), microfibers also consist of natural fibers such as cotton and silk (Barrows et al., 2018). Both types of fibers from natural and synthetic fabrics s are considered pervasive in the marine environment (Carr, 2017; Napper and Thompson, 2016), where they can be released from wastewater treatment plant (WWTP) effluent waters (Carr et al., 2016; Murphy et al., 2016) and through the spreading of sewage sludge on agricultural land (Browne et al., 2011). Despite the effects of microfibers in the marine environment are largely unknown, there is general agreement that they have unwanted impacts on marine organisms (Rochman et al., 2015; Watts et al., 2015) and may be a source of harmful chemicals (Remy et al., 2015; Rochman et al., 2013).

Marine microplastic pollution can be conceptualized as a wicked problem (Hastings and Potts, 2013; Huang and London, 2016; Landon-Lane, 2018) due to the presence of conflicting interests and values, having no single optimal solution or way of testing a proposed solution and being part of bigger systems or 'messes' (Ackoff, 1979; Norton, 2012; Rittel and Webber, 1973). Such complex problems are difficult to tackle with traditional research methods and within individual and separate disciplines, giving rise to a series of new approaches and research methods (Ackoff, 1979; Funtowicz and Ravetz, 1993; Rittel and Webber, 1973), that emphasize systems thinking, interdisciplinarity and multi-stakeholder involvement (Lang et al., 2012).

According to systems thinking, the behavior of a system originates within its structure. Trying to understand the structure is therefore key to understanding how a system might react to various management options and potential solutions (Meadows, 2008). However, identifying how a particular system will react to new information or changes within its structure is challenging as reactions are often delayed and small changes can have big consequences (Meadows, 2008). Advocates of system thinking encourage viewing complex environmental problems in

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a holistic manner by introducing methods that facilitate stakeholder engagement and interdisciplinarity (Rapp Nilsen and Nilsen, 2018; Sedlacko et al., 2015). These approaches help to establish a stronger knowledge base by facilitating group discussion and analysis (Gray et al., 2012; van Vliet et al., 2012). They can also empower stakeholders to monitor and manage complex issues (Reed and Dougill, 2010) and contribute to making systems more adaptable (Gray et al., 2012).

Fuzzy cognitive mapping (FCM) is a form of system dynamics modelling based on peoples' knowledge (Kok, 2009). Compared to other decision making approaches, FCM is particularly suited for contexts that involve high degrees of uncertainty, such as complex environmental issues and linked social ecological systems (Gray et al., 2012; Kontogianni et al., 2012; Mehryar et al., 2017; Page et al., 2012). As a participatory modelling tool, FCM can be used to facilitate knowledge integration of complex environmental issues (Gray et al., 2012; Mehryar et al., 2017; Vasslides and Jensen, 2016) as well as to add structure to workshops and group discussions (Gray et al., 2012; van Vliet et al., 2017; van Vliet et al., 2012; Vasslides and Jensen, 2016). It is also frequently used to investigate different futures through scenario development and simulation (Jetter and Kok, 2014; Kok, 2009; van Vliet et al., 2017). Scenario development in the context of FCM is often not intended as an accurate prediction of the future, but as a way of exploring how a system might react to a set of plausible changes. Thus, insights from scenario development with FCM can be used to facilitate deliberation and to inspire more reflection around change, avoiding the dangerous fallacy of thinking that something will remain unchanged (Jetter and Kok, 2014).

The current study uses FCM to explore and model different stakeholders' perceptions of the complex systems around microfiber pollution in an attempt to form a shared understanding of the issue and identify important knowledge gaps. FCM is also used to develop relevant future scenarios and to analyze the implications of these scenarios from the perspective of the different stakeholders. Since microplastic fibers were first reported as a major component of microplastic contamination (Browne et al., 2011), but few studies have investigated this complex problem in an integrated manner (Gattringer, 2018). This study contributes to fill this gap in the literature by applying FCM to investigate the current problem in an interdisciplinary and participatory manner and reflecting on how this approach can foster co-learning, deliberation and shared understandings on emerging global wicked problems, such as the one at hand.

2. Methodology

2.1. Stakeholder selection and information

Relevant sectors and hence stakeholders were identified based on the findings of previous studies, for example textiles washing being the main contributor to marine microfiber pollution (Browne et al., 2011). The aim was to attain a holistic picture of marine microfiber pollution by including an understanding of sources, path and fate of microfibers, in addition to a broader understanding of the social and economic aspects. Based on this, participants were identified by reviewing the literature on the topic and identifying the main sectors with an interest in and knowledge about different aspects of the issue. This included researchers within the fields of biology, chemistry and materials and nanotechnology, sustainability and R&D managers and experts from textile companies, engineers and representatives from WWTPs, representatives from NGOs working with marine plastic pollution, and people with knowledge about laundry processes in domestic and industrial laundry (Table 1). All participants came from Northern European countries, with the majority from Norway. Participants were contacted through email and invited to take part in the interview and the following workshop. All participants were given a consent form together with a participant information sheet (following the ethical approval by the University of Edinburgh).

Table 1
Stakeholder information for the Fuzzy Cognitive Mapping interview participants.

Stakeholder group	Respondents	Maps	Occupation and organization
Research	6	6	Academic researchers, state agency researchers
Industry	5	5	Textile company representatives
WWTP	5	4	Municipality representatives, engineers
NGO	3	3	International and national environmental NGOs
Washing	2	2	Industrial laundry
Totals	**21**	**20**	

2.2. Data collection – individual mapping

FCMs were collected from May to June 2019 through individual interviews conducted either face to face or through videoconferencing. Interviews took between 30 and 80 min. A total of 21 participants representing 5 different stakeholder groups were interviewed (Table 1). This led to a total of 20 individual FCMs, with one map being excluded from the final results due to quality assurance issues. Data collection followed the steps described in Özesmi and Özesmi (2004). The participants were first given an explanation of the interview process and shown an unrelated FCM as an example. They were then asked a series of open-ended questions designed to establish the variables in their FCMs. The following questions were asked in the order presented:

1. What are the sources of microfiber pollution?
2. Are there any mitigation measures that can reduce microfiber pollution?
3. What kind of effects can microfiber pollution have on the environment once they have been released?
4. Are there any laws or policies that affect the problem in any way? If yes, then which ones?

The participants' answers to these questions formed the variables in their FCMs. Participants were then asked to review the generated list of variables and to add any other variables they considered important to include to describe the system around microfiber pollution. After all the variables were included, participants were asked how the variables related to each other and to draw links between the variables. Lastly, they were asked to indicate whether the links were positive or negative and to signify the strength of the different links by adding between one and three plusses for positive relationships and one and three minuses for negative relationships. If the sample size is sufficiently large the number of variables representing new concepts added in each interview should approach zero in the final interviews, meaning a saturation point for new knowledge has been reached (Özesmi and Özesmi, 2004) (Özesmi and Özesmi, 2004). In this case, variables representing new knowledge were added up until the last interview, suggesting that the saturation point wasn't necessarily reached and therefore the sample size should potentially have been bigger. Deliberation and validation of the community FCM during the workshop (described under) was intended to help address this issue.

2.3. Data collection – collective mapping and scenario development

The second stage of data collection took place through a 1-day workshop in June 2019, where 10 of the participants from the individual interviews took part. In addition, 4 new participants from industry and research took part, giving a total of 14 participants representing all stakeholder groups included in stage 1 apart from NGO. From the beginning of the workshop, participants were split into 3 groups comprising 4–5 participants. Each group contained representatives from as many stakeholder groups as possible, as well as a mix of interview participants and new participants. This was done to facilitate two-way learning and deliberation across disciplines and perspectives, and to introduce new viewpoints into the process. Participants worked in the same groups throughout the workshop.

Prior to the workshop, variables generated from the individual interviews were combined and reduced to a total number of 21 through merging identical or closely related variables (Fig. 1). The individual FCMs were then combined to form five separate stakeholder maps (Figs. S1–S5, Supplementary Information; SI) and an aggregated community map (Fig. S6, SI). The aggregated community map was produced by giving equal weighting to each of the individual stakeholder maps, thus ensuring stakeholders groups comprising higher numbers of members did not determine a greater proportion of the community map. In the workshop, participants were given a copy of the community FCM, which had been digitized in the modelling software Mental Modeler (Gray et al., 2013). The first task in the workshop aimed to validate the community map. To achieve this, workshop participants were given the opportunity to add, remove or change the wording of variables and add, change or remove connections between the variables. They were given printed out versions of the maps and markers to complete this task.

To facilitate group work and discussions, the community map was further broken down into two maps. Map 1 represented aspects related to the consumer phase of the product and so featured variables representing the use-phase of textiles and mitigation measures relevant for this stage of the product life cycle. Map 2 represented the production phase of textile products and so featured variables representing production, policy and regulation and mitigation measures relevant for this part of the system. Variables representing transport routes, fate, and effects were present in both maps. As Map 2 was much more complex than Map 1, one group focused on discussing Map 1 and two groups focused on discussing Map 2. While participants were asked to focus on a particular aspect of the system, they were aware that the various aspects of the system were interrelated. After the workshop, the revised versions of Map 1 and Map 2 were re-combined to form a revised and validated final community FCM.

Using the two break-out maps, the workshop participants were also tasked with identifying a set of variables for scenario analysis. To do this, they were asked to deliberate around the following question: "What will this system look like in ten years?", and to consider what shifts and developments to the system were plausible and relevant from their respective stakeholder groups' perspective. This step went parallel with the validation step in the workshop, and it was up to each group to decide how much time they spent and how they deliberated it. They were asked to consider which variables they thought would change in the next ten years, which was indicated on the FCMs through highlighting specific variables. As the workshop participants were working on two different maps, there were some differences in the variables identified by each group. Potential scenarios were discussed in the same 3 groups. Two scenarios were identified by the research team based on participant notes from these discussions and personal notes taken from the group deliberations in this part of the workshop. To facilitate the inclusion of variables identified by all the groups that would be most affected by changes within the next decade, Scenario 1 is represented by a 'Green Shift' occurring with both consumers and industry (including the textile industry, WWTPs and washing machine manufacturers) and Scenario 2 by increased consumption of textiles and a corresponding increase in textile production. Scenarios were run after the workshop.

2.4. Data analysis

Cognitive maps can be represented by adjacency matrices:

$$A(D) = [a_{ij}] \quad (1)$$

where the variable v_i makes up the vertical axis and the variable v_j makes up the horizontal axis of the square matrix. If there is a link between two variables the weight of this is coded in the matrix (Özesmi and Özesmi, 2004). FCMs from personal interviews can be analyzed individually or combined into stakeholder maps by adding the related adjacency matrices together (Gray et al., 2012; Kosko, 1988).

The FCMs were analyzed based on methods previously described in (Gray et al., 2012; Özesmi and Özesmi, 2004; Vasslides and Jensen, 2016). Briefly, the 197 individual variables generated across all the FCM interviews were listed followed by an iterative process where the variables were categorized and narrowed down. In several cases, the same variable was described by a different name or term in the various individual maps; these variables were identified, allocated a common name and redundant (duplicate) variables were removed. Two variables representing the same concept, but with opposing directions, can be included in an FCM with the same direction by altering the polarity of the interaction (Kim and Lee, 1998; Vasslides and Jensen, 2016). Based on this, variables in the current study with opposing directions, but representing the same concept, were combined and given the direction indicated by most participants. The original 197 variables were reduced to 75 in this process. Next, the least frequently mentioned variables were identified and combined into categories. For instance, all variables pertaining to measures to reduce microfiber release from domestic laundry processes were combined into a single variable called 'Domestic mitigation actions'. This further reduced the total number of variables to the 21 that were used to create the pre-workshop version of the aggregated community FCM presented to the participants. The reduction of variables from 197 to 21 reduced the cognitive effort of participants while enabling a discussion regarding the fundamental components of the system.

By the end of the workshop, new variables were included in the system bringing the total number from 21 to 28. This revised total included both the new variables discussed in the workshop and the division of some existing variables into two variables. In addition, new connections were added to the community FCM and some of the original connections from the pre-workshop version of the community FCM were re-assigned new weights. As a result of the break-down of the pre-workshop map for group work, there were three maps to analyze after the first task of the workshop. The first was the pre-workshop community map that represented the perceptions of the participants taking part in interviews, while the final two maps represented the results from group deliberations in the workshop. Map 1 and Map 2 were combined after the workshop, but as two groups worked separately on Map 2 the workshop generated two separate community maps. The two versions of Map 2 were first combined with Map 1, leaving two post-workshop community maps to be combined with the pre-workshop community map. To represent the perceptions of interview participants and the results of the group work in the workshop, weights allocated to

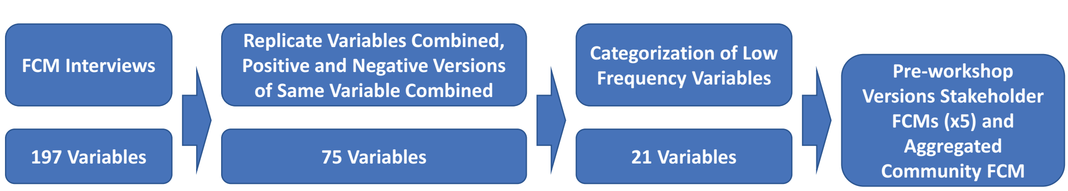

Fig. 1. Flow diagram showing the analysis and streamlining steps applied to the 197 variables generated through the FCM interviews.

connections between variables were averaged across all three maps. As stakeholders were not asked to validate the weights, only a few were changed during the workshop. As a result of this, the pre-workshop community was considered when averaging weights for the post-workshop community map, as well as the fact that not all stakeholder groups were present and worked on both break-out maps.

After the process of FCM categorization and validation had been completed, all maps (stakeholder maps and post-workshop community FCM) were evaluated based on a range of structural indices, including density, centrality, and their level of complexity (Gray et al., 2012; Özesmi and Özesmi, 2004). Variables were also categorized as ordinary, transmitter or receiver, where transmitters are variables with forcing functions or 'givens', receivers are 'ends' and ordinary variables are 'means' (Hage and Harary, 1984; Harary et al., 1965; Özesmi and Özesmi, 2004). The density (D) of a map says something about how sparse or connected it is, and is given as

$$D = \frac{C}{N^2} \tag{2}$$

for maps where variables can have causal effects on themselves, in which case the maximum number of connections possible equals N^2 (Hage and Harary, 1984; Özesmi and Özesmi, 2004). C refers to the number of connections and N refers to the number of variables. Centrality is a measure of the total number of links going in and out of a variable and of the weight of these links (Chytas et al., 2010), that is the sum of a variable's indegree [$id(v_i)$], meaning the total value of links going in to the variable,

$$\mathrm{id}(v_i) = \sum_{k=1}^{N} \overline{a}_{ki} \tag{3}$$

and outdegree, or the total value of links going out of the variable

$$od(v_i) = \sum_{k=1}^{N} \overline{a}_{ik} \tag{4}$$

(Hage and Harary, 1984). Centrality, or total degree [$td(v_i)$] is thus given

$$td(v_i) = od(v_i) + id(v_i) \tag{5}$$

and is a measure of a variables' contribution and connectedness within a map (Harary et al., 1965; Özesmi and Özesmi, 2004). A variable with a total outdegree of 0 and a positive indegree is termed a receiver variable. In contrast, a transmitter variable is characterized by a positive outdegree and a total indegree of 0. An ordinary variable has links going both in and out (Özesmi and Özesmi, 2004).

Lastly, the level of complexity is derived from the make-up of the different kinds of variables in the system; a high number of receiver variables indicate more considerations about potential results or consequences of system structure and leads to a more complex map (Eden et al., 1992; Gray et al., 2012). Contrary to a complex structure, a flat structure may be interpreted as an indication that more choices and different views have been considered within the system (Eden et al., 1992). The ratio R/T, where R is the receiver variables and T is the transmitter variables, is used to determine the complexity of a map (Özesmi and Özesmi, 2004). FCMapper, an Excel-based program, was used for calculation of indices in the current study (Bachhofer and Wildenberg, 2019).

2.5. Scenario analysis

Scenario analysis was based on the identified variables and scenarios discussed in the workshop (Section 2.3). After the stakeholder and post-workshop community maps had been drawn, coded into matrices and added together, they were used to run model scenarios in FCMapper to investigate how the system would change from a steady state under two different scenarios. The steady state is calculated to see what direction the system will take under a no-change-scenario (Özesmi and Özesmi, 2004). This is done by multiplying a steady-state vector, which is assigned a value of 1 for every element in the vector, with the adjacency matrix of the FCM. The new vector created through this process is then transformed into the interval [0, 1] using the logistic function $1/(1 + e^{-1*X})$, before being multiplied with the initial matrix again (Gray et al., 2012; Özesmi and Özesmi, 2004; Zubris and Richards, 2005). This process is repeated until the system goes into a steady state or potentially into a limit cycle of chaotic pattern (Kosko, 1988; Özesmi and Özesmi, 2004). In the current study, the system went into a steady state after 21 iterations for all models. The scenarios are modelled by clamping one or more variables in an iterative process. This provides an indication of how the other components within the system will change under the modelled scenario (Kosko, 1988; Özesmi and Özesmi, 2004).

3. Results

3.1. Stakeholder maps from individual interviews

The five stakeholder maps generated by combining individual FCMs from participants representing the same stakeholder group are presented in Figs. S1–S5 (SI). Variables relating to sources, pathways, environmental fate and effects, and management options were included in all stakeholder FCMs, with variables representing social aspects, environmental aspects, political aspects and technical aspects sources featuring in certain stakeholder FCMs. The structural differences between stakeholder groups are presented in Table 2 and show that the 'Industry' (11.80) and 'Research' (11.00) groups had the highest number of variables. All groups had a similar number of receiver variables (1.50–2.50), but the 'Industry' group (6.20) had a higher number of transmitter variables compared to the other groups (2.33–3.75). The number of ordinary variables varied across the groups, with the highest value for the 'Research' (6.00) group and the lowest for the 'WWTP' (0.75) group. The 'Research' group had both the highest number of connections (17.80) and more connections per variable (1.60) than the other groups. The 'NGO' and 'Washing' groups had more connections per variable (1.38 and 1.24, respectively), while the 'NGO' group had the highest complexity (1.08).

'Microfiber release to marine ecosystems' was the most central variable for all stakeholder groups (Figs. S1–S5, SI). 'Domestic laundry' was a central variable in all maps except for the 'NGO' stakeholder map, while 'Textile consumption and use' was central to both the 'Research' and 'Washing' groups. 'National laws and regulations' was included in all stakeholder maps, being a central variable in the 'Research',

Table 2
Mean and standard deviation of key parameters for each of the stakeholder groups.

Stakeholder group	Research	Industry	WWTP	Washing	NGO
No. of maps, *n*	6	5	4	2	3
Total number of variables	11.00 (2.10)	11.80 (2.95)	7.50 (0.58)	8.00 (2.83)	9.67 (1.53)
Number of transmitters	3.00 (1.79)	6.20 (2.86)	3.75 (1.50)	3.00 (0.00)	2.33 (1.53)
Number of receivers	2.00 (1.10)	2.20 (1.30)	2.50 (1.00)	1.50 (0.71)	2.00 (1.00)
Number of ordinary	6.00 (1.55)	3.40 (2.97)	0.75 (0.50)	3.50 (2.12)	5.33 (3.79)
Number of connections, *C*	17.80 (4.36)	14.0 (5.57)	7.50 (0.58)	10.00 (4.24)	13.67 (5.86)
Connections per variable	1.60 (0.44)	1.15 (0.24)	1.00 (0.11)	1.24 (0.09)	1.38 (0.47)
Complexity	0.60 (0.50)	0.51 (0.50)	0.87 (0.77)	0.50 (0.24)	1.08 (0.80)
Density, *D*	0.20 (0.07)	0.11 (0.02)	0.28 (0.26)	0.19 (0.06)	0.16 (0.04)

'Industry' and 'WWTP' maps. The 'Research' group map contained the most connections (76), while the 'washing' group map contained the fewest variables (12) and connections (17). A detailed description and comparison of the individual stakeholder group maps is provided in the Supplementary Information.

3.2. Community FCM

The final community FCM (Fig. 2) is the result of the pre-workshop interviews and the group discussions in the workshop (Fig. 3). Changes to connections between the following variables were made: 'Consumer awareness' and 'National laws and regulations', 'Environmental toxins' and 'Natural fibers', 'Natural fibers' and 'Environmental health', and 'Microfiber release to marine ecosystems' and 'Environmental health'. The following new variables were added: 'Recycle, reuse', 'Technology development' and 'International laws and regulations'. Finally, the variable 'Stronger materials' was split into 'Sustainable materials' (e.g. reduced fiber shedding, lower environmental impact and fewer production chemicals) and 'Stronger materials' (pertaining to functionality and durability).

In the pre-workshop community FCM, there was a positive connection between 'National laws and regulations' and 'Natural fibers' and a negative connection between 'National laws and regulations' and 'Synthetic fibers'. These connections were identified as being linked, as many actors within the system perceive natural fibers to have a lower environmental impact. As 'Consumer awareness' was considered to have an impact on 'National laws and regulations', this perception was considered to encourage creation of regulations favoring a reduction in 'Synthetic fibers' and an increase in 'Natural fibers'. However, recent findings that natural fibers may also cause environmental impacts (Barrows et al., 2018; Remy et al., 2015) were deliberated at the workshop and participants decided to delete the connections between 'National laws and regulations' and both 'Natural fibers' and 'Synthetic fibers'. At the same time, a new negative connection between 'Natural fibers' and 'Environmental health' was included to represent the new information. The centrality of the 'National laws and regulations' variable was increased, as the participants formed a new agreement about its importance. It was also linked to the new variable 'International laws and regulations' in a reciprocal relationship. Discussions about the distinction between the variables 'Stronger materials' and 'Sustainable materials' led to a new connection between the 'Stronger materials' and 'Environmental toxins' variables based on input from workshop participants with knowledge about the use of additive chemicals, coatings and lamination in the production of textiles.

During the workshop, a total of 28 distinct variables and 113 connections were identified for the final community FCM (Fig. 2), including 7 new variables and 39 new connections. The most central variables after 'Microfiber release to marine ecosystems' were 'Environmental health', 'National laws and regulations', and 'Environmental toxins' respectively in the final community FCM. This marked a notable change from the pre-workshop community FCM (Fig. S6, SI), where 'Textile consumption and use', 'Domestic laundry', and 'National laws and regulations' were the most central variables respectively after 'Microfiber release to marine ecosystems'.

3.3. Scenario analysis

A Green Shift in textile production and consumption (Scenario 1) is characterized by stricter national laws and regulations, increased knowledge leading to improved waste management, industry routines (WWTPs and textile industry) and more sustainable materials (improved recycling/reuse and reduced shedding). The Green Shift also extends to consumers, leading to their increased awareness of the issue. The following variables were clamped to model the scenario: 'National laws and regulations', 'Knowledge through research and monitoring', 'Waste management', 'Industry routines', 'Sustainable materials' and 'Consumer awareness'. Generally, regulation and research are considered important for leading the direction towards a systemic change in current production and consumption systems (Mickwitz et al., 2011), indicating 'National laws and regulations' and 'Knowledge through research and monitoring' are important for a Green Shift to occur. These variables are precursors for 'Waste management', 'Industry routines' and 'Sustainable materials' and stand in a reciprocal relationship with 'Consumer awareness'.

Fig. 4 shows how the variables change following a Green Shift around textile production and consumption based on each individual stakeholder group's perceptions, while Fig. 5 represents the overall perceptions of the entire participant group. The 'Microfiber release to marine ecosystems' and 'Environmental health' variables change the most in both figures. While 'Environmental health' changes more in the community map (Fig. 5), there is a bigger change in 'Microfiber release to marine ecosystems' based on most of the stakeholder maps (Fig. 4). A significant reduction of 'Environmental toxins' in both maps can be considered an unintended consequence of the scenario analysis process. All groups except 'Washing' see an improvement in 'Environmental health' under Scenario 1, while some stakeholder groups (especially 'Washing') see a greater reduction in 'Release of microfibers to marine ecosystems' (Fig. 4). This reduction has a smaller impact on 'Environmental health' in the stakeholder-based model. This may reflect the link between 'Microfiber release to marine ecosystems' and 'Environmental health' not being identified in individual interviews or the variable 'Environmental health' not being identified in some stakeholder maps. 'Microfiber consumed by marine species' and 'Environmental toxins' are also perceived to decrease under Scenario 1.

The Green Shift scenario community map exhibits similar trends to the stakeholder maps, with a clear positive effect on 'Environmental Health' that derives primarily from a significant reduction in the release of microfibers to marine ecosystems (Fig. 2). Other variables perceived to have a significant negative effect on 'Environmental Health' are 'Microfiber release to air', 'Textile consumption and use' and 'Natural fibers'. Overall, a Green Shift leads to a reduction in all of these variables, which contributes to the improvement in 'Environmental health'. The improvement is revealed to be markedly greater for the community-based model than for the stakeholder-based model.

Scenario 2 is defined as an increase in textile production and consumption, which reflects both current and predicted trends (Carr, 2017; Niinimäki and Hassi, 2011). Results from the stakeholder FCMs are presented in Fig. 6 and those from the community FCM in Fig. 7. Overall, the greatest effect of Scenario 2 on the stakeholder-based model is for the variable 'Microfiber release to marine ecosystems', while for the community-based model it is the 'Environmental health' variable. There is also a considerable increase in 'Microfiber release to marine ecosystems' in both models. The 'Industry' and 'Washing' groups perceive the effect to be greater than the other groups (Fig. 6), which is a somewhat unexpected result. Furthermore, the increase was somewhat larger for these groups than the increase based on the community FCM (Fig. 7). The negative effect of Scenario 2 on the variable 'Environmental health' is significantly greater for the community FCM than for the stakeholder FCMs, with only 'Industry' and 'Research' seeing a change in the variable (Fig. 6). Both the community and stakeholder FCMs also exhibit a significant increase in the 'Domestic laundry' variable under Scenario 2.

The 'Washing' group expect greater changes in 'Industrial laundry', 'Domestic laundry', and 'Microfiber release to marine ecosystems' variables, while the 'WWTP' group perceives changes to be relatively small for all variables except 'Domestic laundry', 'Microfiber release to terrestrial systems' and 'Environmental toxins'. Spreading of sludge on fields and microfiber content in sludge were important components in the stakeholder map for the 'WWTP' group, which may reflect greater knowledge about this part of the system. The increase in 'Domestic mitigation actions' and 'Sustainable materials' for the 'NGO' group suggests better knowledge about current trends. This is supported by research indicating that development of sustainable materials is of

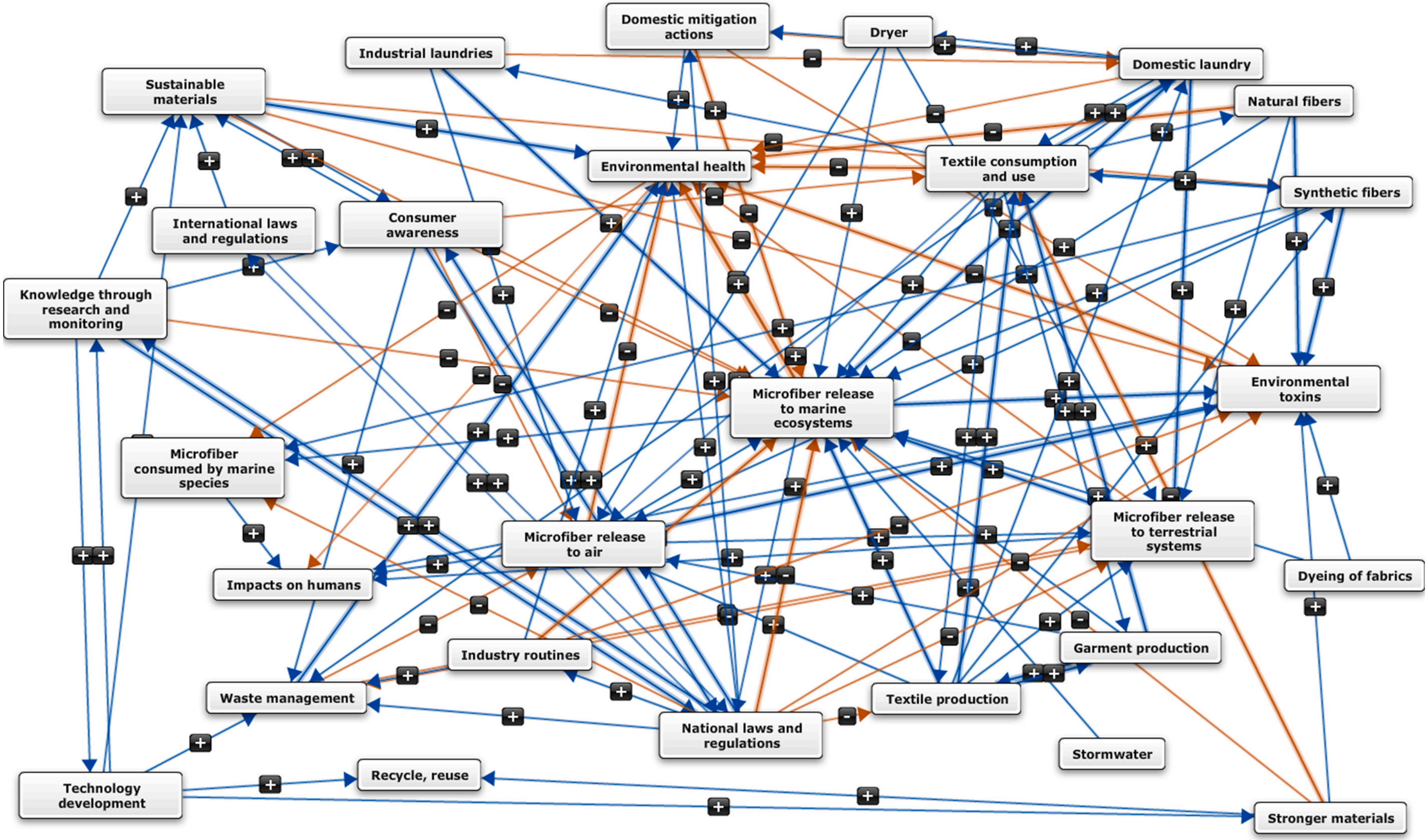

Fig. 2. Final community FCM developed from individual interviews and further revised and validated during the workshop.

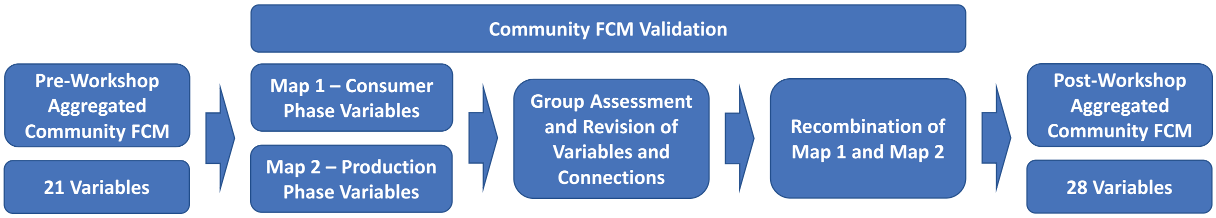

Fig. 3. Flow diagram showing workshop process leading to the development of the revised and validated post-workshop community FCM.

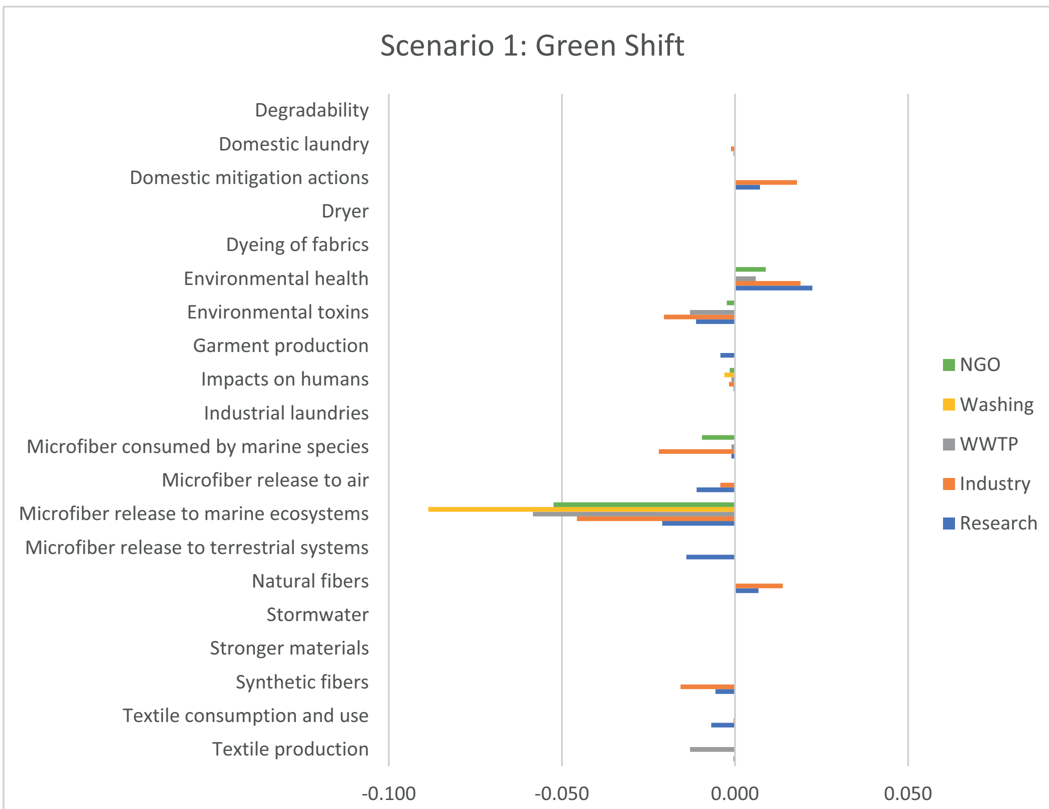

Fig. 4. Green Shift scenario based on the 5 pre-workshop stakeholder maps showing the degree of change from steady state.

increasing focus in the textile industry (Niinimäki and Hassi, 2011).

The community FCM exhibits similar patterns to the stakeholder FCMs, with some variation in the degree of change from steady state. The community FCM shows that an increase in textile production and consumption will lead to a clear increase in microfiber release to marine ecosystems, air, and terrestrial systems, a clear increase in 'Environmental toxins', followed by a clear decrease in 'Environmental health'. Increased production and consumption are also followed by a clear increase in 'Domestic laundry' and 'Industrial laundry'. A slight increase is observed for 'Industry routines', 'National laws and regulations', 'Sustainable materials', 'consumer awareness' and the new parameters 'Technology development' and 'International laws and regulations'. Stakeholder and community FCMs show an increase in 'synthetic fibers' and 'natural fibers', with the highest increase for synthetic fibers. This reflects synthetic fibers accounting for approximately 60% of current global textile fiber production and cotton fibers accounting for 30% (Carr, 2017).

4. Discussion

4.1. Stakeholder perceptions and key uncertainties

There was clear evidence that individual stakeholder groups viewed the system differently, focusing more on aspects directly related to their own core knowledge and experience bases. For example, the 'WWTP' and 'Industry' groups saw 'National laws and regulations' as one of the most central variables, possibly resulting from their work being more affected by this variable and them seeing more clearly how it might affect the other variables in the system. 'Washing' was the only stakeholder group that had 'Domestic mitigation actions' as one of the most central variables, which appears to reflect this group's focus on laundry processes and measures that can be taken to reduce fiber shedding. 'NGO' and 'Research' were the only groups that had 'Environmental health' and 'Microfiber consumed by marine species' among their most central variables. Environmental researchers (highly represented in the 'Research' stakeholder group) primarily investigated the effects of microfibers, while NGOs have a significant focus on communicating risk information to consumers, which may explain the importance of these variables in the respective stakeholder maps.

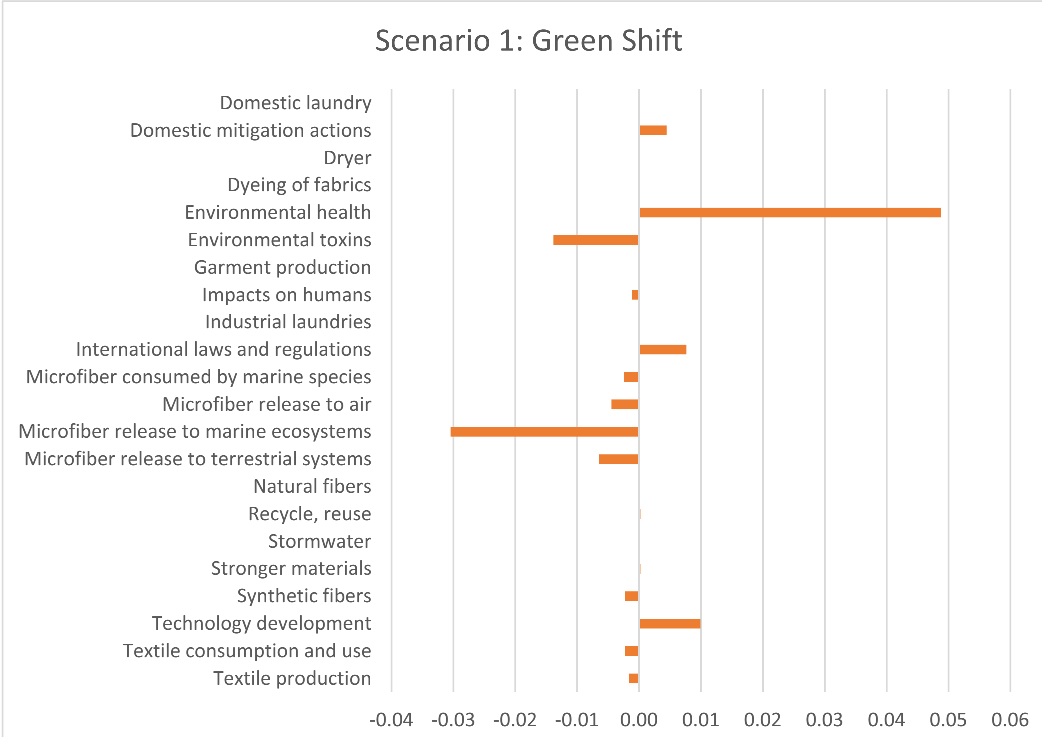

Fig. 5. Green Shift scenario based on community map (after workshop). Shows degree of change from steady state.

Despite individual stakeholder groups clearly focusing on different aspects of the system, they generally agreed that uncertainty was a central aspect. Uncertainty and lack of knowledge were key topics in both the individual interviews and in the workshop. This led to a lot of participants assigning the lowest possible weight (+, or 0.25/−, or − 0.25) to most of the connections as they wanted to avoid assigning high weights where they were uncertain. They also tried to make a clear distinction between the weights they considered strong and the ones they thought were weaker or where they were uncertain. These uncertainties around the system are also found in most studies addressing the topic of microfiber pollution, irrespective of the scientific discipline. For example, Carney Almroth et al. (2018) highlight the need for more research on the temporal and spatial distribution and breakdown of particles in the environment, while Barrows et al. (2018) identified a lack of research on natural and semi-synthetic fibers in the environment. The lack of clarity and research into the social and economic aspects of this type of pollution is also identified (Gattringer, 2018; Villarrubia-Gómez et al., 2018). The uncertainty within the system and around the suggested mitigatory measures might explain the importance all stakeholder groups placed on the variable 'Knowledge through research and monitoring'. It was included as a transmitter variable in all stakeholder maps, meaning it is considered central in driving the system (van Vliet et al., 2017) and its importance was discussed in all individual interviews.

As observed for the individual mapping, uncertainty was also a central topic in the workshop. Several uncertainties were identified during discussion of the community FCM at the workshop, including the uncertainties around the variables 'Synthetic fibers' and 'Natural fibers'. The variables 'Natural fibers' and 'Synthetic fibers' are influenced by the variable 'Textile consumption and use', whether 'Consumer awareness' would lead to a reduction in 'Textile consumption and use', and if 'National laws and regulations' would trigger change in any of these variables. As a result of deliberation during the workshop, the connections between 'National laws and regulations' and the two fiber types were taken away due to the uncertainties around differences in their environmental fate and effect, the potential for both natural and synthetic fibers to serve as vectors for environmental toxins (Barrows et al., 2018; Remy et al., 2015) and the resulting uncertainty about how this information might influence regulation and policy-making.

Uncertainty and a lack of understanding of how the variable 'Consumer awareness' would impact the system was also a topic of constant deliberation during the workshop. A decline in 'Textile consumption and use' and in the release of microfibers to air and marine waters were, for instance, identified as outcomes of increased 'Consumer awareness'. Even though the connections were left within the map after the workshop, they were questioned and discussed throughout. 'Consumer awareness' was considered to have a profound effect on 'National laws and regulations', which was seen as important in driving positive change within the system.

The significant level of uncertainty around the microfiber issue resulted in the 'Knowledge through research and monitoring' variable being emphasized as highly important. This was evident from both the individual interviews and from the workshop discussions. The current study clearly shows that this variable, in conjunction with an increase in 'National laws and regulations', 'Industry routines' and 'Consumer awareness' play a key role for the mitigation of microfiber release to the environment. These findings also serve to underline the need for research on all parts of the system, including economic, social and technical aspects, as well as environmental aspects. This supports the findings of other studies covering similar topics (Gattringer, 2018; Vegter et al., 2014; Villarrubia-Gómez et al., 2018), which highlight the need for interdisciplinarity and research that account for the interdependencies between economic and ecological systems. The findings in the current study provide further validation for this, where the participants identified a need for deeper understanding of how consumer awareness and different kinds of laws and regulations would affect the system for instance.

The variable 'National laws and regulations' is one of the most central in the community map (as well as the 'WWTP' and 'Industry' stakeholder maps), indicating it is perceived to be important within the

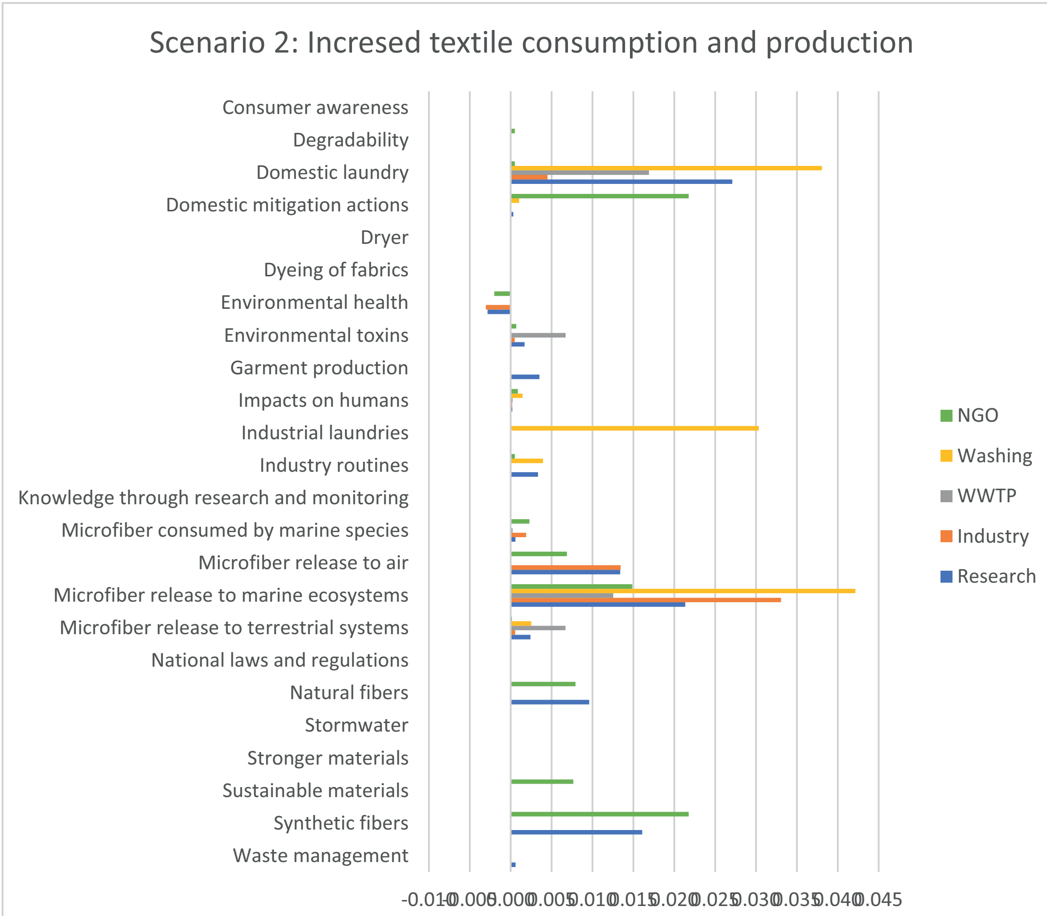

Fig. 6. Increased textile consumption and use based on stakeholder maps. The output shows degree of change from the steady state.

system and a key mitigation measure. Within the systems thinking literature (Meadows, 2008), rules are considered to be high leverage points and are suggested as important tools in changing the current dynamics of production and consumption systems (Mickwitz et al., 2011). One suggested regulation discussed in the workshop and in individual interviews was the use of labels and eco-labelling. However, there is a lack of information and knowledge regarding the design of these approaches (Laitala et al., 2018). For example, the difference between 'Stronger materials' and 'Sustainable materials' was a dominant topic of discussion during the workshop, where the former were defined as more durable and functional materials and the latter defined as materials where fewer chemicals have been used in the production phase and that shed fewer fibers. Although more chemicals are typically used in the production of 'Stronger materials', their durability might make them more suitable for reuse and, in turn, result in fewer fibers being shed. However, some of the steps to make the materials stronger and more durable involve chemicals, for example coatings (Hernandez et al., 2017), as captured by the link between 'Stronger materials' and 'Environmental toxin'. In this regard, and similar to the findings of Carney Almroth et al. (2018), systematic investigation into textile technology was considered important to identify measures that can be implemented in the materials and product design phases to reduce shed of microfibers.

4.2. Contribution of FCM to knowledge integration and new understanding

The FCM development and deliberation process followed in this study shows how different stakeholders can contribute to a more holistic perspective of the system. While textile industry representatives contributed with knowledge about production processes, researchers within various fields provided insight into the known effects of microfiber pollution in the environment and the pathways microfibers can take before they reach the environment. Furthermore, engineers and representatives from WWTPs helped understand the pathways related to sewerage systems and treatment plants in more depth, while 'Washing' and 'NGO' stakeholder groups provided an important insight into laundry processes and the consumer perspective. All stakeholder groups contributed important knowledge about various aspects of the system, which provided a more complete picture of the problem and the way it is perceived, as well as identifying key knowledge gaps. It also allowed for comparison between the perception and knowledge of different stakeholder groups. Similar to previous studies, the current study found FCM to be an efficient tool for (i) knowledge integration across multiple stakeholders from different areas of expertise (Gray et al., 2012), (ii) facilitating and adding structure to group discussions, (iii) serving as a shared platform for knowledge exchange (van Vliet et al., 2017), and (iv) facilitating two-way learning and inspiring new thinking (van Vliet et al., 2012). When applied to the emerging global wicked problem of microfiber pollution, we have demonstrated that FCM is a useful tool for different stakeholder groups to evaluate the problems from their own perspective and knowledge base. Furthermore, FCM helped to identify and provide options for addressing clear weaknesses in the state of the literature, which currently fails to address the multiple dimensions of the topic and the interdisciplinarity needed to tackle the issue as a whole. In this regard, FCM could be a particularly useful tool to understand emerging socio-environmental problems.

The workshop, where the combined FCM from all the interviews was used as basis for discussions, provided a platform for further reflection

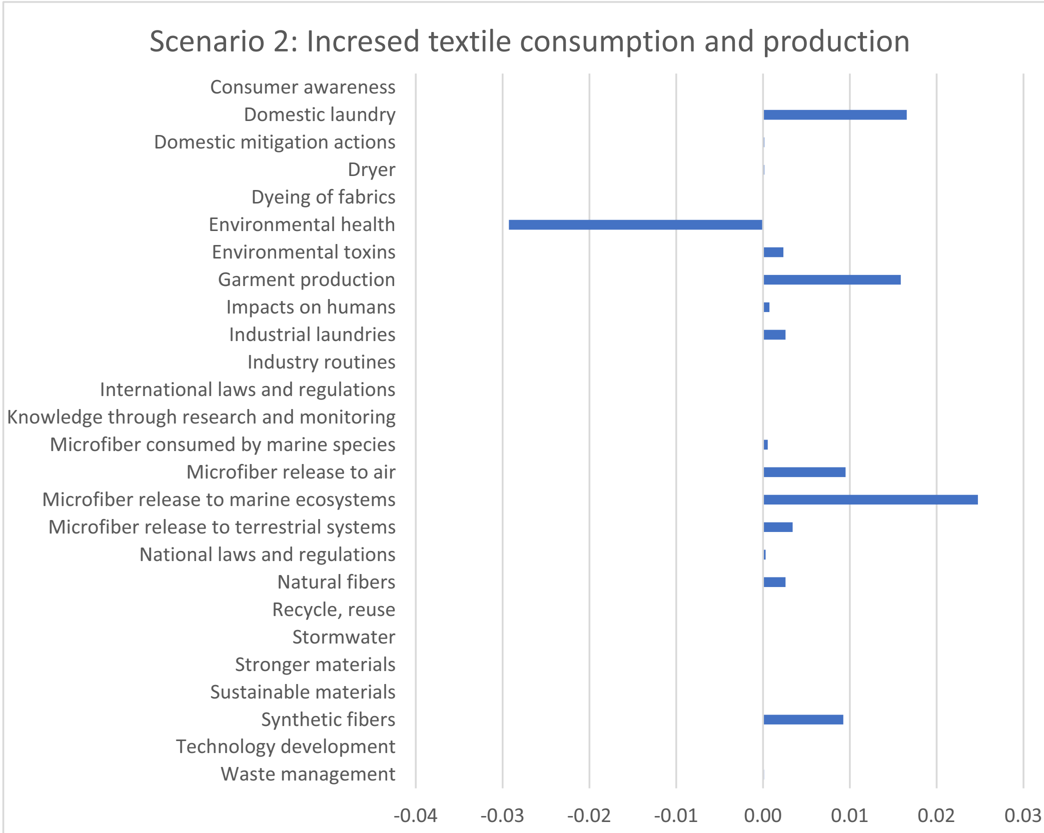

Fig. 7. Increased textile consumption and production based on the community map. The output shows degree of change from the steady state.

and deliberation about the system and its structure. As a result of discussions and knowledge exchange between participants, new variables and connections were identified, while some were moved or deleted. The final community FCM can therefore be considered an outcome of a social process, characterized by reciprocal learning and exchange of knowledge. Example outcomes of this process can be seen in the map through the inclusion of the new variables' and through the altered and deleted connections. We believe that our personal perceptions of the workshop process may add to the interpretation of the resulting FCM maps and data. In general, all representatives from each stakeholder group approached the process in a positive and solution-orientated way, without any clear or strong evidence of specific groups defending any vested interests. There was a common and complementary understanding of the problem and that it would most likely require a combination of solutions across multiple stakeholder groups to achieve a meaningful impact. Interestingly, all stakeholder groups were very open to understanding more about the opportunities and limitations for mitigation actions within the other stakeholder groups.

The pre-workshop FCM proved a useful tool for inspiring new thinking and innovative ideas in relation to microfiber pollution. Based on the results and participant feedback, thinking about the problem as a system and having a visual representation of their perceptions helped participants to view things from a different and broader perspective. The research also showed that the complexity of the maps following the workshop increased, with a larger number of variables and connections. This potentially indicates that these processes allowed for more than aggregation of knowledge that tends to be compartmentalized and enabled a deeper reflection on the implications of drawing connections across the system, moving towards a more holistic systems thinking perspective.

As demonstrated in other studies, FCM proved to be a useful tool in group discussions between different stakeholders, as it provided a common base for considering uncertainties and knowledge gaps and for thinking about measures to address the problem. For example, when FCM was applied to the complex issue of deforestation in the Amazon the method provided the potential to introduce new thinking and broaden the current discussion by introducing new perspectives and topics (Kok, 2009). In this example, previously developed storylines had a very narrow focus which was limited to only one driving force (road expansion), leading critics to deem current research approaches as too simplistic. Current research on microplastic pollution has been criticized for the same reason (Gattringer, 2018), which serves to underline the usefulness and importance of exploring methods such as FCM as tools to introduce new ideas and highlight uncertainties beyond the confines of current debates. In the current study, FCM was found to be a useful tool for allowing different stakeholder groups to evaluate the problem of microfiber pollution and, through a common workshop, come together to share knowledge that can lead to improved understanding at both the individual stakeholder group and community levels.

It is important, however, to highlight some of the limitations of the current study. For example, the sample sizes of the stakeholders are relatively small and may not be sufficient to draw robust statements about the wider stakeholder communities. Furthermore, the lower representation of certain stakeholder groups (NGO and Washing in particular), both in interviews and in the workshop, might have led to important knowledge not being included and deliberated. While all participants also represented textile consumers in addition to their professional roles, it could have been beneficial to have this group more specifically represented within the process given that 'consumer awareness' was identified as a key factor in addressing the problem and facilitating change. An equal representation of all stakeholder groups may have provided a more complete picture of knowledge and perceptions about the system and led to more comprehensive discussions in the workshop. In addition, new variables were identified in every interview until the last one, indicating that more interviews could have been conducted. Although the workshop addressed this to some degree, it would have been beneficial to have talked to more people during the first phase of the project. It is important to highlight that the current study has a strong Norwegian focus, whereas the issue of microfiber emissions and pollution is a global issue. We acknowledge that the findings from the current study cannot necessarily be extrapolated to the global level.

5. Conclusion

The findings of the current study show that microfiber pollution is a highly complex and multifaceted wicked environmental problem and that to address knowledge gaps related to several elements of the system more interdisciplinary and deliberative research is needed. Through integration of various knowledge sources allowed for by the FCM, a more holistic picture of the problem and its uncertainties has been presented and several important knowledge gaps related to different areas have been identified. More interdisciplinary knowledge was also identified as a key factor towards development of regulatory measures given existing uncertainties related to the environmental impacts and to how information and awareness of microfiber pollution translates into action in the system. FCM proved to be a good structuring tool for group discussions and using processes featuring visual representations of the system introduced the participants to new ways of thinking about and viewing the complex issue microfiber pollution. This was evidenced by the increased layer of diversity and complexity added through the number of new variables and connections that resulted from the social processes and reciprocal learning in the workshop. FCM also proved to be a useful tool for researching microfiber pollution and helped address a major weakness in the current literature pertaining to the interdisciplinary and linked nature of the issue.

CRediT authorship contribution statement

Vilde Margrete Salberg: Conceptualization, Formal analysis, Methodology, Investigation, Writing – original draft, Writing – review & editing. **Andy M. Booth:** Conceptualization, Funding acquisition, Project administration, Investigation, Supervision, Writing – original draft, Writing – review & editing. **Susie Jahren:** Conceptualization, Funding acquisition, Investigation, Writing – original draft. **Paula Novo:** Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2022.113713.

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