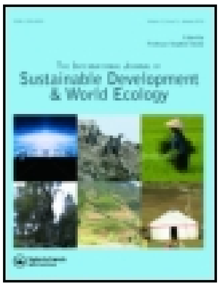

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Trans-disciplinarity required in understanding, predicting and dealing with water eutrophication

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Trans-disciplinarity required in understanding, predicting and dealing with water eutrophication

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Eutrophication remains a challenge for water quality, and leaching of phosphorus (P) from agriculture remains usually the determining factor as point source emissions of sewage are mainly under control. The Morsa watershed, southeast of Oslo, is a case in point. In spite of abatement actions during the past 20 years, the total concentration of P in the lake has decreased less than expected, causing growing frustration and scepticism among farmers. Hydro-biochemical interactions between phosphate (PO_4) and calcium, aluminium and iron in soil and water have produced unexpected results. Decline in acid rain deposition over Norway has reduced the leaching of aluminium into water. This has caused a loss of an important fixation and removal of P by sorption to precipitating aluminium oxy-hydroxides. The combination of more precipitation and higher winter temperatures causes more flushing of P from surface soil horizons. Furthermore, water-logged soil loses much of its ability to hold PO_4 in that iron is reduced, thereby allowing more P to escape. Farmers proved to have good agronomical knowledge and are taking part in an active network for spreading of agricultural practices. Reducing the amount of P in fertilizers was accepted fairly easily, whereas minimal autumn tillage has been a much harder task to implement. Therefore, just applying economic incentives will not do; developing basic environmental literacy with an ability to understand feedback loops and rebound effects is necessary. Following this, interaction between science and stakeholders is required, calling for trans-disciplinary research and trans-disciplinary processes.

Keywords: eutrophication; phosphorus; environmental drivers; trans-disciplinary; knowledge; learning

1. Introduction

Decades after the Brundtland-report 'Our Common Future' (World Commission on Environment and Development 1987), the challenge of bringing the development onto a sustainable path is still daunting, both within different fields of science and at different scales: natural environments from biotopes to large-scale eco-systems are experiencing stress, and similarly economic systems and social systems at different scales are also experiencing different types of stress (United Nations Environmental Programme 2013). These are not just challenges for human communities and societies, but basically also challenges for science and for the interaction between science and society. As underlined by Scholz (2011), science is necessary for society to grasp and cope with the complexities of environmental feedback-loops and rebound effects, but the mode of knowledge production ought to change from science for society to science with society; thereby bringing trans-disciplinary research and trans-disciplinary processes centre stage.

In this article, we are engaging with the challenges of sustainable development of our natural resources by discussing water management at the scale of a watershed in Norway within the frames of the European Water Framework Directive (WFD). The WFD asks for the development of good ecological quality of surface waters, and in order to achieve this, scientists and environmental managers need to understand the hydro-biogeochemical mechanisms governing fluxes of nutrients to aquatic environment and how anthropogenic pressures influence these mechanisms. Phosphorus (P) is commonly the main governing factor for eutrophication in freshwater. Moreover, since most point sources, such as discharges from sewage, have been removed or is being removed in Western Europe, the diffuse loading of P from agriculture remains as the main cause for not achieving the requirements of the WFD in agricultural districts.

Abatement actions targeting eutrophication often fail to generate the expected amelioration of the water quality. This is generally explained by continued flux of phosphate (PO_4) from large pools accumulated in the agricultural soils and lake sediments. Still, it is a paradox when sewage sanitation and constructed wetlands do not generate a clearer immediate effect on Total-P fluxes. Such abatement actions are bound to also have instant effects through reduced leaching of access PO_4, reduced erosion of Particulate-P and capture of different P fractions in buffer-zones and constructed wetlands. A possible cause may be that environmental pressures increasing P fluxes to the watercourse have changed concurrently, such as increased rainfall amount and frequency, increased winter temperatures, increased tile drainage and decrease in

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acid deposition (Vogt 2012). Consequently, the task for natural scientists is to better understand conceptually the hydro-biogeochemical processes governing the leaching and transport of different P fractions and evaluate the effects such regional changes in the environment have on these processes.

Numerous abatement actions have been taken against the leaching of P to water and the resulting eutrophication in our study area, Lake Vansjø and the Morsa watercourse, southeast Norway. Generally, water in Norway is plentiful, although periods of less precipitation might cause temporary and regional/local shortages. Therefore, Norway ought to be in the range of Jowsey's (2012) continuous natural resource (CNR), except for cases of pollution. The case of eutrophication might be seen as pushing the water resource into the state of potential natural resource (PNR), requiring actions to bring it back to CNR. Noticeable cultural eutrophication in Morsa started already in the 1950s and has since then escalated due to population growth and intensive agriculture. In 1999, the Morsa Project was launched (MORSA 2013), following the initiative of seven municipalities in the catchment area. The aim was to implement coordinated abatement efforts that would lead to enduring improvements in the conditions of the watershed. Over the past 20 years, approximately 125 mill EUR are spent on abatement actions in the Morsa watershed to alleviate the eutrophication problem. A bundle of measures have been applied including both sewage redevelopment and changing farming practices. In this article, the focus is on farming practices in which both mandatory and voluntary measures have been implemented: these abatement actions include changed agricultural practices (i.e. minimal autumn tillage, especially to avoid ploughing on land strongly prone to erosion, and the use of mineral fertilizers with less P content, as well as to avoid ploughing water ways in the fields) and establishment of physical barriers (i.e. establishing vegetated buffer strips adjacent to streams cutting through agricultural fields; constructing ponds functioning as wetlands adsorbing Bioavailable-P and catching silt and thereby P bound to the particles). To illustrate the scale in which these measured have been implemented in the Morsa watershed, we can use the application of P fertilizing which was almost halved from 2004 to 2007 (Øgaard & Bechmann 2010). These measures have, however, still not managed to bring the water back to a 'good ecological status'. In fact, there is no clear reduction in Total-P levels in the main water basin of Lake Vansjø, the Storefjorden, whereas in the smaller western Vansjø, which has suffered from more severe eutrophication, there only appears to be a slight recovery since a flood in year 2000 (Skarbøvik et al. 2011). In order to meet the requirements of the WFD the famers around Lake Vansjø were recently invited to (voluntarily) sign up for taking further actions along the same lines for a certain economic compensation. The main focus of WFD is on price-mechanism and economic incentives as means for achieving the wanted ecological status. Although municipal mayors and government officials populating the watershed board generally are positive to taking measures, there is a challenge in achieving a continued collective action among the farmers since they do not see the expected immediate effect of their efforts, as the levels of Total-P have not declined as expected in the lake. They are therefore reluctant to continue along the same path. This is especially pertinent as one might even have to venture into even stronger measures; 'picking the high hanging fruits, not just the easier available low hanging fruits'. In light of this it is interesting that the Morsa project also has applied measures focussing on learning and knowledge, thereby providing a case for discussing science and the role knowledge. The Morsa watershed case thus proves to be an interesting case for both natural science and social science, and the interaction between science disciplines as well as science and society.

Two key societal questions that will be addressed are (1) How to achieve the necessary motivation among farmers to continue and even take new sub-optimum measures? (2) What is the current environmental literacy among farmers, and what are the prospects of developing the necessary literacy? In order to establish the necessary basis for answering questions like these, the present state-of-art research on eutrophication applied on the Morsa watershed and Lake Vansjø is presented, as well as the thinking among farmers by addressing concrete measures and farming practices.

Generic statements among Morsa farmers are as follows:

> Everything our very clever teacher at Kalnes agricultural school taught us was correct wisdom at that time, to pour phosphorus onto our fields, and to do autumn tillage; both practices are now in disgrace.
>
> In my opinion, the Morsa Project has been really successful in developing norms for the content of phosphorus in the soil, and that we could reduce the use of phosphorus without causing less output (—) as long as you are not taking it too far.
>
> The most difficult measure to understand, and the most difficult measure to implement, has been minimal and zero autumn tillage; the practice of autumn tillage has been so deep-rooted, and there is no way that abandoning it will not cause lower output as it makes winter wheat impossible.

It is imperative to understand the reasoning and reasons underlying these two last statements: some measures, although challenging conventional wisdom, are fairly easily adopted by the farmers, whereas others face long-lasting resentments. This directly relates to the challenge of achieving a sustainable management of water resources; understanding the barriers and thresholds in society towards implementing required abatement actions, as well as how to handle the interaction between different actors as part of environmental rebound effects.

The research presented in this article contends that the apparent lack of direct effect of abatement actions is due to concurrent regional changes in drivers of P flux that has led to an confounding increased 'background' flux of P to the lake (climate change, increased use of drainage pipes) and reduction in an important P removal mechanism (precipitation by Al leached by acid rain), disguising the effect of abatement actions. This infers that the abatement actions most likely have had the desired effect and that the water quality would thus have been considerably worse today if it had not been for the implemented actions. This might then serve to eradicate the scepticism among farmers regarding the effect of their measures, thereby potentially removing an important barrier in society towards implementing further abatement actions. Consequently, it is important to take into account this interaction between science and society, bringing the issue of trans-disciplinary research and trans-disciplinary processes to light as way forward for developing environmental literacy among important stakeholders as well as facilitating collective actions for reducing the flux of P to the lake; an issue we are addressing below.

2. Theory, methodology and empirical basis

2.1. Theory

Following Scholz (2011, p. 15), we define environmental literacy as 'the ability to appropriately read and to utilize environmental information, to anticipate rebound effects, and to adapt according to information about environmental resources and systems and their dynamics'. So, what has to be 'read' and what kind of eutrophication feedback loops and rebound effects are we addressing? The short version of the story is that Total-P in the water environment may be conceptually and analytically divided into three fractions: Bioavailable-P consisting mainly of orthophosphate ions (PO_4), dissolved natural organic bound P (DOM-P) and Particulate-P, the latter two constituting at least partly potential secondary pools of Bioavailable-P. Bioavailable-P is commonly the limiting factor for algae growth in the aquatic environment due to poor mobility and thus limited input of P from the terrestrial environment (Schlesinger 1997). In soils, the PO_4 is occluded in the mineral crystal lattice and organic material or strongly bound to aluminium (Al), iron (Fe) and calcium (Ca). In addition, there are pools of more or less easily soluble or de-sorbable P (Reddy & Delaune 2008). The Al and Fe form positively charged oxy-hydroxides that sorb PO_4 anions. Furthermore, the Al^{3+} and Fe^{3+} constitute a binding bridge between the net negative charged surfaces of clay or organic matter coating on minerals and the PO_4 anion. Flooding causes decreased redox potential, allowing for reduction of Fe(III) to Fe(II), and eventually sulphate (SO_4) to sulphide (S^{2-}) capturing the Fe(II) as FeS. In some strongly eutrophic lakes and in sewage treatment plants, Al solution of Alun ($AlSO_4$) is applied in order to precipitate out phosphate (Cooke et al. 1993). This is because the Al^{3+} at pH between 6 and 8 hydrolyses and precipitates out as amorphous oxy-hydroxides, adsorbing the phosphate and eventually ageing into highly insoluble $AlPO_4$ mineral. During base-flow conditions, runoff is mainly fed through ground water discharge containing generally low concentrations of P fractions, except through drainage pipes in agricultural fields. During heavy rainfall, overland flow causes substantial erosion from tilled agricultural land. Prolonged rain saturates the soils allowing for a predominant sub-lateral flow through the shallow forest floor (Mohr 2010) or plough layer (Ap) in agricultural soils (Opland 2011).

Admittedly, full understanding of these processes is not any plain sailing, but grasping the essence of what is going on would help develop the necessary environmental literacy among farmers and other stakeholders; thereby facilitating informed discussions of what actions to take. Starting with (theories of) learning and knowledge, it is instructive to distinguish between *experiential learning* which is knowledge created by an iterative cycle linked to learning-by-doing; *transformative learning* through a reflective process of instrumental learning, task-oriented problem solving and determination of cause and effect links, as well as *communicative learning* through communication of feelings, needs and desires; and *social learning* through group-based iterative reflections facilitated by sharing experiences, ideas and environments with others (Keen et al. 2005; Armitage et al. 2008). Several researchers have argued for the dominant position of social learning, especially under particular challenging conditions, as for instance the introduction of the WFD and coping with climate change (e.g. Ison et al. 2007; Steyaert & Jiggins 2007; Pahl-Wostl et al. 2010). On the other hand, Orderud and Winsvold (2012) found that all types of learning are in play among municipal officers preparing for climate change adaptation, and disregarding for instance experiential learning would hamper social learning to take effect, or even make it fail.

Closely linked to this is the idea of learning cycles, with experiential learning being the basis for *single-loop* learning cycles of correcting errors and improving performances within the frames of established practices. The next step is a *double-loop* learning requiring changes (of different magnitude) in existing assumptions for practices, and, lastly, *triple-loop* learning cycles of transforming the structural context of practices and also changing of governance norms and practices, thereby requiring social learning (Armitage et al. 2008; Pahl-Wostl 2009). However, from the same basic idea, Scholz (2011) identifies three cycles of environmental learning linked to the term of feedback loops. Here the experiential learning makes up a primary feedback loop with adjusting strategies according to short-term changes in the environmental system. Next, two secondary feedback loop learning cycles are identified: one of *awareness learning* with the human system changing the internal model of the human – environment interactions in the light of long-term environmental change; and the other based on *reflective learning* with 'reframing the internal model of human – environmental interactions, including the building of values and norms' (Scholz 2011, p. 514).

The term social learning brings the human society centre stage, whereas the feedback loop learning and human –

environmental interactions are meant to bring human society and the natural environment centre stage; that is, making social learning part and parcel of trans-disciplinary (environmental) research and processes. Adding to the complexity is the insight of Polanyi (1966) on tacit knowing and knowledge: we know more than we can tell, and that tacit knowledge is part of scientific knowledge alongside the explicit and coded knowledge of science. Furthermore, learning and knowledge are part of path dependent processes, and characterized by more or less lock-in regarding ways to act and handle problems. This applies to all types of actors; farmers, public authorities, scientists, etc. Entering triple-loop learning or reflective learning also means the need for changing tacit knowledge, and changing tacit knowledge is a more thorough process than changing the coded knowledge. From this, it also follows that we are not dealing with any 'rational economic man', but more likely actors characterized by bounded rationality and acting on the basis of not just economic self-interest, but on both self-interest and disinterest; in short, on the basis of broad bundle of motives and reasoning.

2.2. *Study site and methodology*

This study is an integral part of the trans-disciplinary Eutropia project (Vogt 2013) (Research Council of Norway project no. 190028/S30) studying watershed eutrophication management through system-oriented process modelling of pressures, impacts and abatement actions. The studied site is the Morsa watershed in the southeast of Norway. Dominant land use is forest (80%), followed by agricultural fields (15%). Unconsolidated marine deposits dominate and are influenced by land heaving after the last ice-age, leaving behind rock outcrop on the ridges, sand on the slopes and accumulations of marine clay in the valley bottom and low lying areas surrounding the lakes. Typically, agricultural land is found in the gently sloping or flat lowland areas. The land-use pattern causes runoff from forests to usually mix with drainage from agriculture before flowing into the eutrophic lake (Shekobe 2012). Most of the runoff from agricultural fields is through drainage pipes installed in marine clay layers (Opland 2011). The use of tile drainage was augmented in the 1970s and 1980s.

The main study focus has been on the lake Western Vansjø, experiencing eutrophication problems, though concentrations of Total-P have declined since a flood in 2000. Data from a state monitoring programme along with project data are assessed through six Master thesis studies (Mohr 2010; Opland 2011; Gebreslasse 2012; Parekh 2012; Desta 2013; Weldehawaria 2013) and used to calibrate models. Major water chemistry and P fractions in nine streams draining local watersheds differing in ratio of forest and agricultural land use (Parekh 2012), the lake (Gener 2010), as well soil-water from different horizons in forest soil (Mohr 2010), have been monitored with emphasis on discharge episodes from 2009 to 2011. P pools and physiochemical characteristics are measured in soils from forest (Mohr 2010) and agricultural (Opland 2011) site, in addition to a synoptic soil study throughout the forested land in the Morsa watershed (Desta 2013), and in sediments from the nine monitored streams and a small lake (Sæbyvannet) in the watercourse (Łukawska-Matuszewska et al. 2013). Laboratory experiments studying the effects on P fractions of mixing forest runoff with drainage from agriculture have also been conducted (Shekobe 2012). Most physiochemical parameters in soil and water samples were analysed according to standard ISO methodology if available or as referred to in the sited Master thesis studies. P fractions are determined by detecting PO_4 in samples before and after filtration and/or digestion; i.e. Bioavailable-P is found in filtrated undigested sample while dissolved organic P is determined as the difference between PO_4 in digested unfiltered and filtered sample. Total-P is determined in unfiltered digested sample.

For the social science studies, the methodology has been qualitative, covering document studies of minutes from the Morsa watershed committee/executive board and in-depth interviews with representatives of the watershed board and with farmers. The analysis in this article is mainly based on 26 interviews with farmers. The interviews were semi-structured and lasting from 1 hour to about 3 hours. An interview guide was designed, comprising open-ended questions allowing the interviewees to elaborate on their responses and opinions. Except for one, all interviews were recorded and transcribed; most of them amounting to about 15,000 words. The selection of farmers was assisted by people with very good local knowledge assuring that the interview objects were representing the whole watershed area though with more farmers residing closer to Lake Vansjø than at outskirts of the watershed. Furthermore, the selection of interviewees was aimed to incorporate farmers that were having different production, like grain, vegetables, and husbandry; running relatively large farms and small farms; full-time farmers and part-time farmers; old and young; and highly educated and without much formal education. And some were known to be critical towards the Morsa project, while others were known to be more supportive, and some were unidentified in this respect. In short, the interviewees covered a broad range of farmers.

3. Analysing and discussing findings

P is the main determining factor fuelling eutrophication processes in aqueous systems, but we should also recognize that P has become one of the necessary components for high global agricultural output which is required in order to feed a rapidly increasing world population; a population also having larger per capita food consumption. Furthermore, under current technological conditions our fossil P resources available for industrial production are limited as we are extracting P from its solid form of its geological cycle. Consequently, it is sound long-term environmental policy to reduce the consumption of P, although making the usage of P sustainable is currently not possible.

Convincing farmers to reduce the content of P in mineral fertilizers is, as the above quote expressed, one of the gains of the Morsa Project. Still, it should be recognized that this has not mainly come about because of anyone subscribing to the 'think globally and act locally'-slogan. The following statement reflects upon the reasoning among farmers:

> Well, I guess I am most of all thinking that Phosphorus is an expense. When you are buying mineral fertilisers, you are not thinking that it is a limited resource (—) this autumn, when I ordered mineral fertilisers from the dealer, I cannot say it was the global stock of Phosphorus that was the main focus, I don't think so.

Nevertheless, farmers turned to mineral fertilizers with less P in spite of this new type of fertilizer being (temporarily) more expensive due techno-economic conditions. The farmers' motivations for reducing the usage of P were instead related to local environmental conditions; that is in general thinking locally and acting locally. One exception to this was one of the organic farmers in the area, but also conventional farmers show an understanding of the big picture:

> We know it is a lot of phosphorus in the ground (—) and along ditches we find a lot of phosphorus bound to aluminium and other metals. So, how should we manage to retrieve it for use again? That is surely a big challenge.

In short, the farmers in the study area have a local outlook, not worrying so much about global P resource conditions. But they are concerned about managing to feed the growing population in the world, and also the use of pesticides. The gradually dwindling rock resource stock of P is expected to be solved by retrieving more energy demanding (and thus more expensive) P from sediments, etc. Moving from this insight in the farmers' perspective, the analysis and discussion below proceed to lay out the science of P fluxes in the Morsa watershed which is central for farmers' actions. On this interdisciplinary basis, the back curtain is given in order to proceed with directing the attention to learning and knowledge, attitudes and opinions among farmers.

As a general background for the findings reported, analysed and discussed below, we know that the sulphur deposition has decreased substantially in areas previously suffering acid rain in the Nordic countries (Skjelkvåle 2012). Due to this the non-marine SO_4, which in acid lakes in southeastern Norway in the 1980s constituted the dominant anion charges, has decreased by 81%. This has contributed to a doubling of the concentration of dissolved organic matter (DOM), while leaching of inorganic labile aluminium (Ali) has declined (Monteith et al. 2007) to a quarter over the past 30 years in fresh water in Norway (Skjelkvåle 2012). Furthermore, the amount and intensity of precipitation in the region has generally been above average and the average winter temperature has been about 2°C above the norm (–4°C) during the past 25 years (Met.no. 2013).

Turning to the P process, Particulate-P constitutes the main fraction of Total-P in the studied streams (40–80%), especially in streams draining some agricultural land (Parekh 2012). This P fraction is not bioavailable and not much of this Particulate-P is found in the lake water as most of it readily settles in the river delta sediments (Gener 2010). Furthermore, internal loading of Bioavailable-P from the sediments is previously assessed not to be an important source in the lake as the concentrations of P in the sediments are found to be low (Andersen et al. 2006). The question is therefore whether the flux of this P fraction contributes significantly to the eutrophication. On the one hand, Gebreslasse (2012) found that P pools in the lake sediments were lower than what was found in the stream sediments, implying that Particulate-P is a source of Bioavailable-P through desorption from particles during settling. This is conceivable as the concentration of dissolved PO_4 in the lake is much lower than in the P-sources (soils and streams) due to grazing of Bioavailable-P by algae. Contrariwise the capacity of the particles to sorb PO_4 is far from exhausted (Łukawska-Matuszewska et al. 2013). This issue is thus unresolved and therefore the subjects of a recently started Master study. It should nevertheless be kept in mind that one-sided abatement actions reducing particle loading may be counter-productive on the eutrophication as it may decrease P scavenging in the stream as well as enhance flux of P from sediments due to decreased dilution and burial of P in the sediments. If in fact the dominant Particulate-P fraction has minor effect on the Total-P in the lake, then the doubled substantial background P loading of DOM-P from the 80% forested land may play an important role in sustaining a high background Total-P loading to the lake (Parekh 2012). Blankenberg et al. (2008) estimated that 39% of the Total-P loading to Lake Vansjø was due to background flux. Since DOM-P is the dominant P fraction in background forest drainage (Mohr 2010), the doubling of DOM concentration over the last 30 years is conceived to have led to a significant increase in the present background loading of Total-P to the lake. This DOM-P may in the lake partially be directly bioavailable and partially be made bioavailable through being photo-oxidized into more bioavailable forms.

Many farmers that were interviewed pondered about the role of forest in loading of P, and this partly relates to the feeling of achieving a fair distribution of responsibility for the observed conditions in the lake, their knowledge about processes in the environment and the role of urbanized areas.

> Now the water is draining quickly out of forest areas after it has been raining as it is drained by ditches, and it goes straight into the river system. I think much of the phosphorus ending up in Vansjø is coming from areas that are not being fertilised, such as forests and other areas.
>
> We convinced them to take samples from a small forest lake ahead of our fields to compare with after our fields, because we had the feeling that something did not add up, and then it turned out that the phosphorus content in the forest lake was very high, but it has not been any big focus

> on this. It did not fit; the forest area should not be any problem
>
> If you want to measure the background leaching, you have to use virgin forest areas, but that forest is also changing due to climate change and other things (—) we will have nutrient runoff due to accumulation and dissolving of organic matter. We can observe this when we are hiking in the forest area; how fine the moss might be in the pine forest, and then how logging causes the ground flora to change.

Run-off from forest area has been a priority for the Eutropia project. Our findings indicate that the sum of inorganic and organic P in the Ap layer of the agricultural fields were between 1 and 2 g P/kg, respectively (Opland 2011). This is high but lower than what was found in forest floors on ridges and slopes, which contained very large pools of P (1.5–4.0 g P/kg). Likewise, highly elevated concentrations of DOM-P were measured in the throughfall deposition under the canopy and forest floor soil-water (up to an average of 150 and 100 μg P/L, respectively) (Mohr 2010). During discharge episodes, high concentrations of all P fractions were measured in the stream. This is due to the enhanced shallow sub-lateral water flow-path through the Ap horizon and P-rich forest floor flushing directly into the stream, bypassing the adsorptive capacity of the plant root zone and deeper mineral soil layers. Overland flow and increased flow velocity also allows for enhanced Particle-P transport through erosion of soil and stream banks, and re-suspension of sediments. A clear temporal co-variation is thus observed between discharge intensity and Total-P concentration in all the streams (Parekh 2012). In fact, 75–81% of the annual Total-P flux occurred during the 36 days with highest runoff (Opland 2011). It is therefore reasonable to assume that the above average amount and intensity of precipitation in the region during the past 30 years (Met.no. 2013) have contributed to an increased flux of Total-P to the lake. Furthermore, hydrological years with frequent melting spells during the winter gave a higher Total-P flux in the streams compared to years with enduring sub-zero winter temperatures (Opland 2011). This might be explained by that runoff episodes during winter have a greater potential for P transport due to that autumn tilled soils are more susceptible to erosion, and due to more overland flow caused by poor water infiltration and storage capacity of the frozen soil. Furthermore, the mobilized Bioavailable-P from enhanced plant lysis in the fall and mineral weathering is not assimilated en route during the dormant winter period. A 2°C higher floating average winter temperature in this region with an average winter temperature of only –4°C (Met.no. 2013) has thus led to more frequent winter discharge episodes during the past 20 years. This has likely also contributed to an increased flux of P to the surface waters, disguising further the effect of abatement actions.

Much of the P in the soils is found to be bound to Fe(III) both in agricultural land (Opland 2011) and in the forest (Mohr 2010). Reducing redox conditions during prolonged periods with water saturated soils, such as during floods, causes mobilization of PO_4 as Fe(III) is reduced to Fe(II) (Holtan et al. 1988). When iron is reduced it is followed on the redox ladder by reduction of sulphate (SO_4) to sulphide (S^{2-}), enabling the precipitation of pyrite (FeS), allowing more orthophosphate to escape (Roden & Edmonds 1997). This may explain why significant elevated concentration of bioavailable PO_4 was measured in water samples collected in the lake in 2011 (Parekh 2012). It is hence speculated that the peak in Bioavailable-P flux after the flood in 2000, and the slow recovering trend since then is partly due to this mechanism and partly due to enhanced desorption due to dilution.

From the interviews with farmers, it is found that many of them have a good basis for understanding this message, but it is also important to acknowledge that presenting findings like these face some challenges:

> 'Look, the water is crystal clear; it is not any leaching of phosphorus,' my father told me. 'Yes, but you do not see the phosphorus, it is invisible' I responded to him, continuing 'phosphorus might be bound in humus and soil particles, but although the water is crystal clear it might still be phosphorus in it'. They do not understand it; a farmer in his seventies, born on the farm and with barely 9 year in school. They are good farmers but when it turns microscopic they do not follow; they believe what they see, nothing more.

Drainage pipes are an important transportation route for P from agricultural soil to surface waters (Opland 2011). This is partly due to rapid transport of P from the P-saturated Ap horizon down through soil macro-pores to the tile pipes, and partly due to erosion of P rich (0.75 g P/kg) and apatite containing (Gebreslasse 2012) marine clay soil around the tiles. Furthermore, according to local farmers, the pipes are known to be regularly clogged by iron-oxyhydroxides, implying a massive mobilization of Fe(II) and thus likely PO_4, from the soils to the pipes. On the other hand, tile drainage decreases flooding and sub-lateral and overland flow, thereby decreasing the loss of P during periods of high rainfall amount. The net effect of the increased use of tile drainage is uncertain, though it is likely that it may have augmented the flux of P over the past 30 years.

Most streams in the watercourse drains extensive upland forest region before flowing down through agricultural land. Acid-forested streams were efficiently neutralized upon mixing with less than 20% runoff from agricultural land use (Parekh 2012). High content of DOM was also found to be converted to particle form in streams draining mix land use (Parekh 2012; Weldehawaria 2013). Laboratory experiments confirmed that when Ali and DOM rich runoff from forest is mixed with seepage from agriculture a substantial precipitation of dissolved PO_4 as well as DOM-P occur (Shekobe 2012). Declined leaching of Ali from the predominant acid sensitive forest headwaters has therefore led to less co-precipitation of Bioavailable-P. P bound to Al is considered a final sink, though P bound to Fe(III) may be mobilized under reducing conditions in bottom of the lake and in the sediments. This loss of PO_4 removal mechanism due to the decline in acid deposition can thus constitute a key explanation for why measures against eutrophication since the 1980s apparently have not given the expected effect (Vogt 2012).

Simulated effects of implemented abatement actions on the 15% agricultural land in the watershed are, according to very preliminary model runs, limited to only 10–15% reduction in Total-P loading. If so, then the effect of the concurrent changes in environmental pressures governing increased P leaching may very well account for the lack of apparent response to the abatement actions. Embedded in these linkages, we see feedback loops and rebound effects, and as underlined by Scholz (2011, p. 439) 'coping with higher order feedback loops is key for complex system understanding' and 'this capacity is a key component of "sustainability learning" '.

Turning to abatement actions, many of the farmers show a strong environmental conscience and a wish to do environmental sound farming, although also admitting they are part and parcel of forces beyond their control. The interviews identified autumn tillage as a rather contested measure. Also other abatement actions are debated: (1) the wetlands were generally considered positive because farmers 'see how much soil that is deposited in those wetland ponds', but on the other hand, some farmers, who from the very beginning were questioning the effect of these ponds, conclude 'now the wetland pond is there, and, bottom line, I see it is a beautifying element in the cultural landscape'; (2) Most farmers accept that the buffer strips along water courses are reducing runoff of P and they have established buffers zones, but there is some resentment because they are often a hassle, making field work less effective, and some also experience erosion more or less eating up the buffer zones; making them question why not any measures are being taken against the erosion; and (3) not ploughing waterways in the field is generally considered a hassle, and debated as something making farming less effective.

> Those simple changes, as for instance making a fertiliser plan are minor changes, and they are not any problem to handle. Most of it has made us better farmers; we are sort of not just doing things by force of habit anymore. The biggest change, though, is minimal and zero autumn tillage. Well, we are doing better now, but we had some difficult years during the transition from having autumn tillage all over, to keeping parts of the fields in stubble: choosing the right moment for different tasks; having the right machinery and equipment; and controlling and inhibiting weeds. There were a lot of strange fields around. Now we have had ten years of gaining experience and acquiring knowledge, but much more machinery and equipment is needed; more expensive as well. A lot of good things, but the regulations are rather inflexible.

So, why is minimal or zero autumn tillage generally considered a big change and still causing resentment? The short answer is that it forces farmers to make fairly large changes in how and when different tasks are conducted. The following quotes illustrate the problem from the perspective of the farmers.

> Let's take this field; it is 240 acres, and very good winter wheat soil. Here you see patches of erosion class 3.[1] Previously we had a lot of winter wheat on this field, ploughing up and down, and so on. Well, it does not make sense to plough in-between the patches of erosion class 3, see? It has to be harrowed, and then the output is quickly 100 to 200 kilo lower per acre. And if you are going to sow winter wheat after just harrowing, you have to do it in August–September, but if you are ploughing, you can sow until September 15th; the soil gets much better when you have those two additional weeks. It is just nonsense doing harrowing in early September with the late autumns we have nowadays. And it is a rather long distance from these patches of erosion class 3 to the creek; no run-off will end up in the creek anyway; those who made these erosion maps have just looked at the contour lines.

> Minimal and zero tillage leaves a lot of straw on the surface of the fields, and this is an infection source because fungi are propagating on these straws; the stubble; making spores and propagation organs that are ready to attack next year (—) myco toxins and fusarium are rather toxic (—) they had a lot of reduced tillage in US, causing a lot of problems because fusarium is spread by the wind.

> Minimal tillage causes smaller crops; I am fully convinced about this. Some research tells us that it is about the same output with minimal tillage (—) my experience is that the difference is much larger, and the reason is that when doing minimal tillage, you have to start much later in spring. The research assumes you are sowing at the same time (—) if you have to postpone your spring work for one week, it has considerable consequences for your output. In addition, soil that has not been ploughed dries very slowly, and you very easily get soil compaction. This causes lower oxygen content in the soil, and then poorer uptake of nutrients by plant later in the year. Consequently, more nutrients are being leached to water because you are following a certain fertilizing plan assuming a certain uptake of nutrients, and not achieving this uptake causes more leaching of fertilizers.

Adding to the last argument is that when ploughing clay rich soil, it is necessary to carefully plan the sequences of ploughing and harrowing in order to avoid drying and forming of big soil clods. On the other hand, a long-term effect of minimal tillage is more humus content in the top layer of the soil which should be good for clay rich soil, but it takes rather long time for the humus to accumulate. All things considered, the tillage issue seems to defend its character of being a kind of double-loop or even triple-loop learning, or in Scholz (2011) terms awareness learning and reflective learning.

The question then is how farmers are learning to adjust their practice, and, furthermore, which role science play in this respect. Are farmers having confidence in the message presented by researchers? Our findings are telling us some important lessons in this respect. First, the learning process among Norwegian farmers must be said to be very systematic, and most farmers are generally active in trying to learn from science and develop their agricultural and environmental competence.

First, being a good farmer is about having practical skills. Mostly all interviewees point out that having a formal education is not a necessary precondition for being a good farmer, but it is also claimed that

> If you do not have the formal competence, it will take longer time before you sort of are able to interpret what you actually are doing (—) someone will never become good farmers because they do not manage to transfer theory into practice, but someone are understanding theory and also managing the practical stuff (—) but I also think that farming in the future will become more knowledge based, and demanding good theoretical knowledge and practical skills.

Following this, it is necessary to recognize that farming is a combination of tacit knowledge and coded knowledge. Theoretically, to know that the soil has to be suitable for ploughing is rather easy, but actually transferring this into practice is quite another task, demanding a lot of experience and knowledge that is not easily expressed literally, or codified. The same goes for when to add pesticides to inhibit weeds or mycotoxins. Furthermore, doing ecological agriculture is claimed to be even more a sport of tacit knowing and knowledge.

> You might learn some ecological agriculture by reading literature, but you have to gain practical experience, make some mistakes (—) you have to wait until the soil is sufficiently dry; you have to wait until the soil is sufficiently warm; and until the soil is suitable for the plough, and as a rule of thumb this is after your conventional farming neighbours have finished, washed their equipment and parked it; then it is time, then you can start your work. In fact, you have to 'feel' the soil, use your spade and dig and look how things turn out: 'no, it is too cold, have to wait' (—) if you miss this when doing ecological farming; entering the field one week too early, the seeds will not grow until after two weeks, and then you have already lost to the weeds; you have missed the train already before the seeds start growing.

This means that learning within farming is a combination of several of the learning categories outlined above: without experiential learning (the learning-by-doing) doing farming is futile, but you also have to be capable of reasoning and changing course on the basis of your experience; entering the cycle of awareness learning or double-loop learning as described above. And, lastly, exchange of experiences and explaining these experiences is necessary because so much depends on actual practising, and sometime this requires reflective learning, or social learning. These features are readily seen in the farming learning network. Both formal and informal channels are necessary elements, and also combined; that is, formal channels facilitating informal exchange of information.

> Many of the active farmers are members of the Agricultural Advisory and Experimental Society; we subscribe to the internet service, receiving weekly information during the season; and we take part in 1-day workshops organised by the Experimental Society and convened on local farms. And of course, we have the informal information exchange between neighbours and farming colleagues, but the information we receive from the Experimental Society is based on real world practice (—) I read Norwegian agricultural journals, and of course, the information we receive from the co-operatively run distributor of farm goods, Felleskjøpet is important. But again, it is first of all the Experimental Society.

> The basic learning pillar was running on the heels of my father since I was 10 years old, but it is necessary to learn that what was correct at that time is not correct today (—) then it was to attend the Agricultural school. Later, I became member of the Agricultural Advisory and Experimental Society, and the Experimental Society is in a way the fundament because they have updated knowledge all the time (—) when they have courses, it is a must to attend (—) they get information from research about pesticides; which is banned and which is legal; they test how small doses we can use and still get the necessary effect (—) on the other hand, the producers of machinery and equipment are good at telling us that we need the products they are selling.

Of particular interest is the role of the Agricultural Advisory and Experimental Society. In co-operation with farmers, they arrange practical tests. Furthermore, they organize meetings focusing on particular production types, and these meetings are convened on local farms. Consequently, it is a formal information channel, but by convening the meetings on local farms, informal information exchange is facilitated. The work by the Experimental Society is also said to be instrumental in convincing farmers to change to mineral fertilizers with less P content.

> We have discussed this [using less P] among us, and with the Experimental Society, and many competent persons have told us it should work, and then we have guarded ourselves by testing and monitoring of the output and the quality. With the assistance of the Experimental Society we learn whether the theory is correct. The Experimental Society is very much trusted by farmers, and with them taking part we expect very quickly to get feedback if things are going wrong, enabling us to adjust the course.

This also indicates confidence as well as trust in research, and some farmers explicitly express confidence in research and science. However, many farmers express scepticism towards researchers and science which apparently is a paradox, but is important to acknowledge and understand when considering the role of science in relation to policy-making and implementation of measures.

> The question is whether you can have confidence in what researchers tell you. Who has asked for the results? You can get whatever information you want from a researcher, isn't so? (—) We have asked for research, but if we had hired the researchers we wanted, what kind of results had we then got? I am not sure about it, but I think a little bit like this

> It is always of interest to know who pays for research, who are those behind the scene governing any research project?

> (—) my impression is that research in Norway differ rather much from research in other countries regarding runoff from agricultural land (—) each research report is asked for by someone, and although I am not paranoid on this, I think it is a fact that this to a certain extent will influence on the results, at least in some cases I think it is like this (—) it is not that I think researchers are cheaters, but the conditions for the research make it like this (—) then the conditions for the answer you wants is already established. Asking others to do similar research would be good.

These two quotes point at a basic distrust in research, and at the end of the day also the role played by science in the process of establishing a factual basis and explaining what is going on. In addition, scepticism and distrust is raised against measures being introduced by public authorities, and then it is partly about research and public authorities acting together, but also about public authorities using results from research.

> The aim was to remove leaching of nine tons of phosphorus per year after the first decade; don't know whether they have managed to remove half of it; as I said, we don't know anything. They cannot just keep on spending resources on measures without the wanted effect of stopping phosphorus from ending up in Lake Vansjø.

> My motivation for taking actions is not 100 per cent. In my opinion, they present some strange conclusions, and sometimes I have the feeling that they have been using data as it fits them. I was very puzzled by the way they presented phosphorus unions and such things (—) it is not that I doubt what the researchers are doing and the results they present, but an uncertainty about what actually is making it turn one way or the other

> Yes, we may lose respect for measures, and perhaps rightly so (—) new findings are presented which may change previous conventions, and if they want to sustain respect, they have to change regulations and measures when new research is presented. If they don't (—) and instead just push ahead along the old track, I and many other farmers will start questioning and wonder what is happening. Updated knowledge is important and avoiding politics to overrule. And arguing that what was shall always be, and so on (—) it has to be knowledge based; that is the basic rule

According to Stokke (2006), the Morsa project is generally considered a success, and this conclusion is confirmed by our own research: managing to bring together people representing different actors and by establishing a sound scientific basis persuading all municipalities in the watershed, (most) farmers and households to take part in the work of reducing losses of nutrients to the Vansjø lake. But as the above quoted statements illustrate, the interaction between science, public authorities and farmers is potentially a breeding ground for conflicts of different magnitude. The above statements might tell about discontent due to lack of involvement, but it is also important to underline that many farmers are positive to a cooperation and interaction with science.

> We have to distinguish between the role of a researcher and a farmer. We have an understanding of issues related to farming (—) working together with researchers is very useful (—) someone giving a lecture on one or several topics, and afterwards we have a brainstorming.

> It is not always the case that the researchers are right, I might very well say. Sometimes I as a farmer might see consequences the researchers do not see (—) I must say the results presented by researchers have been important, and researchers have showed up in meetings and discussing these.

Consequently, the challenge seems to be developing a form of interaction that facilitates the development of environmental literacy as described above among all central actors and stakeholders.

4. Discussion and conclusions

Central questions in this study have been how to achieve the necessary motivation among farmers to continue and even take new, sub-optimum measures. The answer to this is argued to be that it is necessary to ensure that the farmers possess good environmental literacy. The follow-up question then is how the state of current environmental literacy among farmers is and what the prospects are for developing the necessary literacy. One of the main findings from the natural science research is that the water quality in the lake had been much worse without the abatement actions taken by the farmer. Game over, it is just to post the happy message on internet and farmers will kowtow, we might conclude. But as should be evident from the above analysis, the game is not that easy, although the findings surely will help pave the way. Adding to the challenges is that more sub-optimal abatement actions are likely to be necessary in order to reach the goal of the WFD.

The learning and knowledge approach revealed different fate for the two most important abatement actions: reducing content of P in mineral fertilizers and shifting to minimal or zero autumn tillage. The success of the fertilizer case came about through a combination of different types of learning. The knowledge presented by the Experimental Society demanded transformative learning among farmers, and this was achieved by organizing social learning through field days on farms in the area, with local farmers attending and learning about new practices. Reflecting on this knowledge, farmers entered the phase of experiential learning by applying mineral fertilizers with less P content on their own fields, making the new knowledge part and parcel of their tacit knowledge of how to run their own fields. Knowledge is one of the cornerstones underlying farmers' motives for taking actions, and farmers have a strong production mentality; that is, farmers are motivated by producing food and achieving a large output as well as good quality. The minimal or zero autumn tillage case has not been that successful despite a clear message from research claiming similar agricultural output levels (e.g. Riley 2006, 2010). The message from science is challenged by that the farmers do not achieve similar output levels when trying to adopt the new practice, and thus the measure runs counter to their production mentality. Some might claim that this is just about increasing the economic compensation, and a good number of research hold on to economic incentives as *the* measure (e.g. Zhang et al. 2011, in this journal), but the issue is not that easy either. It also has to make sense to farmers, and this is about learning and knowledge, and the knowledge the farmers are supposed to learn has to prove to be correct when tested out by concrete agricultural practice, as well.

One aspect of this is that the new knowledge in order to become integrated into farmers' practice has to enter the tacit part of their knowledge which means that the changes are interiorized and fully accepted. The second argument then is that this requires applying all types of learning (experiential, transformative, communicative and social). It is not sufficient to initiate network and social learning in order to broadcast 'mission achieved'. The different types of learning form a whole. Following this, it might also be necessary to conceive single, double and triple loop learning cycles as nested, and forming a whole. As a case in point, farmers looking back on changes in their agricultural practice consider most of these changes as small, but all the small steps are adding up to 'quantum leaps' when taking the longer view, and very often it is about technical changes. Correspondingly, the more fundamental changes being part of triple loop learning cycles might be dissolving into a multitude of more common single loop learning cycles when they are being implemented.

However, the environmental dimension is not yet fully introduced; that is, making environmental literacy part of farmers' agronomical knowledge. In the terminology of Scholz (2011), this might mean awareness learning as well as reflective learning of basic feedback loops. Concretely, farmers have entered awareness learning and some are possibly in the phase of entering reflective learning about how reduced P application works within their own fields, whereas they for different reasons have not done so in the case of minimal or zero autumn tillage. On the other hand, in order for this knowledge to become true environmental literacy, farmers have to acquire a comprehensive understanding of the role of P and the processes eventually causing algal blooms in Lake Vansjø. Several farmers are trying to conceive of what is going on and a few have achieved a basic understanding, but acquiring good hydro-biogeochemical understanding of the processes governing P leaching, transport and impact is no plain sailing. It is also a question of how deep understanding is required for farmers to develop confidence in research results and the scientific message. Our claim in this respect is that farmers need to develop a better, and deeper, understanding than is currently the case. However, our interviews with farmers in our study area tell us that they have gained a certain understanding of the processes going on: for instance, they are generally well aware of the fact that P leaching is higher during incidences of strong rainfalls and in particular flood events, and following this, that actions to prevent leaching might have to be taken before flood events take place.

Developing environmental literacy is demanding. For example, the interaction of agricultural practices with the hydro-biogeochemical interactions between phosphate and calcium, aluminium and iron in soil and water quickly makes things challenging. Furthermore, being successful in developing environmental literacy might still not be sufficient. Power games among different and conflicting and contradictory interests might derail the process of implementing measures and having farmers comply with those measures. The fact that farmers are asking whose interest research is representing, and questioning the premises for research, indicates an understanding of the overall processes they are part of; a sort of political literacy. Addressing this is beyond the scope of this article, though, but we fully agree with the necessity of extending our analysis to cover this area as well. As Scholz (2011) underlines, when bringing trans-disciplinary research and trans-disciplinary processes into sustainability science, intergenerational and intra-generational justice enter the scene. But what actions can help achieve a sufficiently developed environmental literacy?

Environmental literacy is about learning and knowledge, and direct actions for improving the literacy are related to different forms of learning. This means all types of learning referred to above: the experiential learning, as well as transformative and social, or the awareness and reflective. Dissemination of scientific environmental knowledge made understandable for different target groups are necessary, and this work should be taken very seriously and not something to be done on spare time and late in the evening. Exemplifying with the Morsa Water District, this would comprise continuing today's practice of disseminating information to members of the board, as well as subgroups, but it would also mean engaging in a broader dissemination for farmers and letting farmers join the subgroup on farming. Furthermore, an active use of the Agricultural Advisory and Experimental Society for linking environmental knowledge to agronomical knowledge is central. In this way, combining experiential learning-by-boing with awareness learning and reflective learning (transformative learning and social learning) is facilitated.

However, although dissemination of scientific environmental knowledge is necessary, it might not be sufficient: for one thing, other types of knowledge, as local and contextual lay person knowledge might play a part, but the institutional structure for dissemination, learning and use of knowledge is also decisive; and our message is that trans-disciplinary research and processes might contribute in this regard. That is, the legitimacy of the message is also a necessary condition for environmental literacy to come into effect. And with this conclusion, we also claim that the information deficit theory (Blake 1999) is insufficient to explain the lack of proper environmental actions.

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Note

1. As part of the policy measure of introducing minimal autumn tillage, agricultural fields were classified into four erosion classes according to field gradients, with class 4 having the steepest gradient. Later class 4 and 3 were merged.

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