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Cycle du carbone et mares : Impact des changements climatiques sur le cycle du carbone dans les mares de petite taille


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Titre : Impact des changements climatiques sur le cycle du carbone dans les mares de petite taille

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Les auteurs de cette recherche ont signé une attestation sur l'honneur de non plagiat.

Formation par la recherche, Projet de Fin d'Etudes en génie de l'aménagement et de l'environnement

La formation au génie de l'aménagement et de l'environnement, assurée par le département aménagement et environnement de l'Ecole Polytechnique de l'Université de Tours, associe dans le champ de l'urbanisme, de l'aménagement des espaces fortement à faiblement anthropisés, l'acquisition de connaissances fondamentales, l'acquisition de techniques et de savoir-faire, la formation à la pratique professionnelle et la formation par la recherche. Cette dernière ne vise pas à former les seuls futurs élèves désireux de prolonger leur formation par les études doctorales, mais tout en ouvrant à cette voie, elle vise tout d'abord à favoriser la capacité des futurs ingénieurs à :

- Accroître leurs compétences en matière de pratique professionnelle par la mobilisation de connaissances et de techniques, dont les fondements et contenus ont été explorés le plus finement possible afin d'en assurer une bonne maîtrise intellectuelle et pratique,
- Accroître la capacité des ingénieurs en génie de l'aménagement et de l'environnement à innover tant en matière de méthodes que d'outils, mobilisables pour affronter et résoudre les problèmes complexes posés par l'organisation et la gestion des espaces.

La formation par la recherche inclut un exercice individuel de recherche, le projet de fin d'études (P.F.E.), situé en dernière année de formation des élèves ingénieurs. Cet exercice correspond à un stage d'une durée minimum de trois mois, en laboratoire de recherche, principalement au sein de l'équipe Dynamiques et Actions Territoriales et Environnementales de l'UMR 7324 CITERES à laquelle appartiennent les enseignants-chercheurs du département aménagement.

Le travail de recherche, dont l'objectif de base est d'acquérir une compétence méthodologique en matière de recherche, doit répondre à l'un des deux grands objectifs :

- Développer toute ou partie d'une méthode ou d'un outil nouveau permettant le traitement innovant d'un problème d'aménagement
- Approfondir les connaissances de base pour mieux affronter une question complexe en matière d'aménagement.

Afin de valoriser ce travail de recherche nous avons décidé de mettre en ligne sur la base du Système Universitaire de Documentation (SUDOC), les mémoires à partir de la mention bien.

REMERCIEMENTS

Nous remercions l'ensemble des personnes qui nous ont encadrés et qui nous ont consécré du temps dans ce projet de recherche.

Nous tenons tout particulièrement à remercier notre directrice de recherche, Madame Séraphine GRELLIER, maître de conférences à l'Université de Tours, pour sa disponibilité et pour son aide dans notre travail. Merci pour cet accompagnement et pour avoir répondu à toutes nos questions.

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Introduction

It has been scientifically proven that humans influence the climate system and that anthropogenic greenhouse gas emissions are the highest in history (Pachauri et al., 2015). These greenhouse gases will cause warming and lasting changes in all components of the climate system (Pachauri et al., 2015). This climate change translates first of all into successively warmer decades at the Earth's surface, including a warming of 0.85 [0.65 to 1.06] °C during the period 1880-2012 (Pachauri et al., 2015). These changes are manifested on inland freshwater wetlands by a change in precipitation and more frequent or more intense disturbance events (droughts, storms, floods) (Bates et al., 2008). In addition, with increasing temperatures, there is an increase in evapotranspiration processes in rivers and subsequently feeding problems in nearby wetlands (Brooks, 2009)

In this review we are particularly interested in the case of ponds, which can be temporary or permanent wetlands.
It is only since the 21st century that we are interessed in the effects of climate change on small freshwater aquatic ecosystems (Ali et al., 2016). However, the whole continental waters, which represents only 2.2 to 3.7 % of the Earth's surface, processes the same amount of carbon as the oceans (Holgerson, 2015). Moreover, small ponds, that is to say with a surface area of less than 0.01 km², represent 16 % of the total surface area of the world's lakes, which in turn represent 4 % of the unglaciated land surface (Yvon-Durocher et al., 2017). It is therefore interesting to know what climate changes involve for the functioning of ponds, given that their importance in the carbon cycle is increasingly recognized, particularly their role as carbon storage (Hornbach et al., 2017).

Studies have already been conducted on temporary wetlands in general, it means it doesn't focus on one type in particular, to define what they are and their ecological and economical role (Calhoun et al., 2017). They are small, shallow systems that dry out periodically or unpredictably. They play a major role in hydrology and biogeochemistry and particularly in flood prevention by reducing flood peaks through their buffering role (Calhoun et al., 2017). Temporary wetlands also allow carbon sequestration as well as denitrification, transformation of pesticides, etc. (Calhoun et al., 2017). They are also hotspots of aquatic plant and animal biodiversity. In France, for example, temporary pools represent 0.05% of the territory but include 35% rare species and 5% protected plants (Calhoun et al., 2017).
Wetlands can act as a carbon source or sink depending on their defining characteristics. It has been shown that wetlands do not emit methane when saturated with water (Kayranli et al., 2010). Moreover, permanent vegetalisation of wetlands allows a more important carbon sequestration than the release in the form of CO_2 (Kayranli et al., 2010). It is also important to note that wetlands and especially their soil and sediments are the largest carbon sinks (Kayranli et al., 2010). However, in the context of climate change, wetlands, especially ponds, are becoming increasingly temporary with longer summer seasons, earlier snowmelt and higher temperatures, or even with intentional human drainage (DelVecchia et al., 2019). Thawing or drainage conditions related to temperature increase promote carbon emissions (Kayranli et al., 2010).

Finally, it is important to understand the carbon fluxes from wetlands and mainly small ponds which represent 8.6% of global lentic surface area, but account for 15.1% of total CO_2

emissions from lentic systems (Holgerson and Raymond, 2016). The study of carbon fluxes in ponds will allow to adjust the current global carbon budget, especially because climate change is affecting pond hydrology (DelVecchia et al., 2019).

The objectives of this review are :
- to analyse the bibliometry of the main studies related to the subject and present the tendency of past and present studies,
- to analyse how climate change affects the different parameters structuring ponds and what are the implications for carbon fluxes and greenhouse gas emissions,
- to identify gaps in the current knowledge about carbon fluxes in relation to climate change in small ponds.

1) Material and methods

All the articles found are from accessible documentary resources of the university library of Tours but also and mostly from CNRS databases, such as Web Of Science.

Firstly, we used english keywords to best target articles and reviews related to the topic (notably "pond", "carbon cycle", "climate change", “organic matter”). We’ve chosen according to the relevance (to our point of view) of the article, i.e. for this first part we have selected only a few scientific articles (10 in total last year) in order to appropriate the subject and to globally understand the current knowledge. Then, we used both bibliography from articles and more specific keywords for example “Effects of atmospheric CO2 on aquatic Plants”. When too many articles were suggested, we selected "manually" the most relevant articles by reading first the titles and then the abstracts of those that seem the most interesting. Finally, we kept for this review 41 articles, reviews and documents related to the subject. We summarized all of our research in the table below (Table 1). It should be noted that some items were provided to us by our tutor Mrs. Grellier and are therefore not referenced in the table.

After reading the abstracts, the relevant articles are stored using ZOTERO, a software that organizes and references all the documentation efficiently. Finally, once the articles are summarized as best as possible in order to facilitate the review process, the articles are categorized according to 3 parameters : hydroperiod, temperature and atmospheric CO2.

Table 1 : Reference of bibliographical research

Research date	Keywords used	Number of results obtained	Search from the bibliography of an article	Selected article	Number of times cited in the database
29/01/2020	pond - carbon dioxide - climate change	77	/	Yvon-Durocher et al. 2017	18 (WOS)
			/	Atwood et al. 2015	4 (WOS)
02/02/2020	pond - climate change - carbon - organic matter	118	/	DelSontro et al. 2016	44 (WOS)
03/02/2020	ponds - carbon cycle	675	/	Hornbach et al. 2017	/
			/	Ali et al. 2016	0 (WOS)
			/	Drzewicki et al. 2018	/
12/02/2020	/	/	Atwood et al. 2015	Shurin et al. 2012	132 (WOS)
21/02/2020	ponds - carbon cycle	675	/	Holgerson 2015	39 (WOS)
09/03/2020	/	/	Holgerson 2015	Natchimuthu et al. 2014	35 (WOS)
03/04/2020	ponds - organic matter	/	/	Hervé 2018	/
01/10/2020	pond - climate change - carbon dioxide	180	/	DelVecchia et al. 2019	66 (WOS)
			DelVecchia et al. 2019	Brooks et al. 2009	120(WOS)
			Brooks et al. 2009	Brooks et al. 2000	126 (WOS)
				Bauder et al. 2005	57 (WOS)
				Brooks et al. 2004	77 (WOS)
				Pyke et al. 2005	32 (WOS)
	pond - climate change - carbon cycle - review	11	/	Marcé et al. 2019	23 (WOS)
			Marcé et al. 2019	Holgerson et al. 2016	224 (WOS)
				Bastviken et al. 2011	742 (WOS)
				Martinsen et al. 2019	5 (WOS)
				Catalán et al. 2014	23 (WOS)
				Gilbert et al. 2017	10 (WOS)
13/10/2020	/	/	Martinsen et al. 2019	Bates et al. 2008	/
				Fromin et al. 2010	43 (WOS)
			Yvon-Durocher et al. 2011	Whiting et al. 1993	558 (WOS)
			Whiting et al. 1993	Lemon et al. 2019	/
			Lemon et al. 2019	Foyer et al. 1984	/
22/10/2020	/	/	Holgerson 2015	Laurion et al. 2010	149 (WOS)
23/11/2020	effects of atmospheric CO2 on aquatic plants	576	/	Shi et al. 2020	2 (WOS)
			/	Hussner et al. 2019	6 (WOS)
			/	Liu et al. 2016	7 (WOS)
			/	Van Kempen et al. 2016	7 (WOS)

2) The state of research about carbon cycle in ponds

All the articles that have specifically studied ponds have been gathered in a table Annexes. Via this table we can observe several characteristics on ponds that are studied in carbon cycle scientific articles. This information is represented by these figures below :

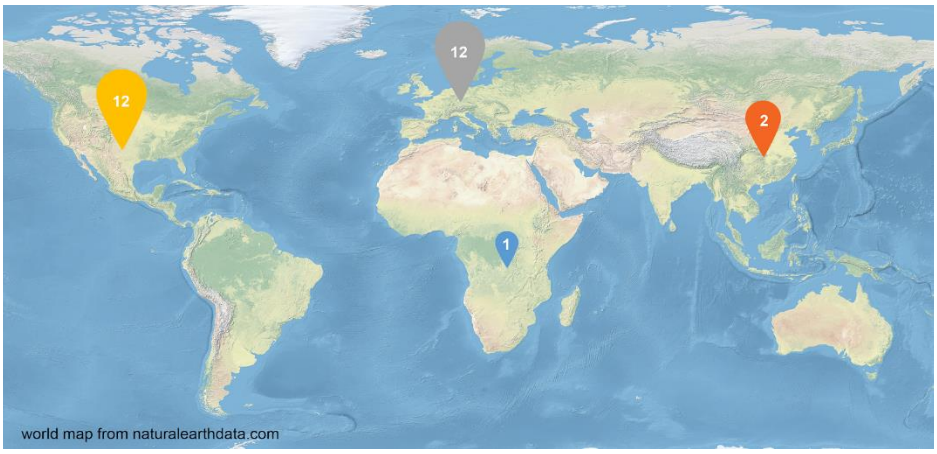


Figure 1 : Number of ponds studies by continent

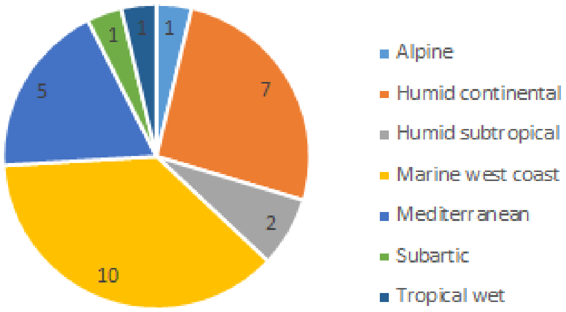


Figure 2 : Number of ponds studies by climate

It appears that studying ponds is complex because of their great diversity. However, all the ponds listed in these articles are not represented in the same way. Thus, in Figure 1, a greater number of articles study ponds in the northern hemisphere (North America and Europe) and in a predominantly marine west coast climate (10 articles)but also humid continental (7 articles) and mediterranean (5 articles) climate (Figure 2).

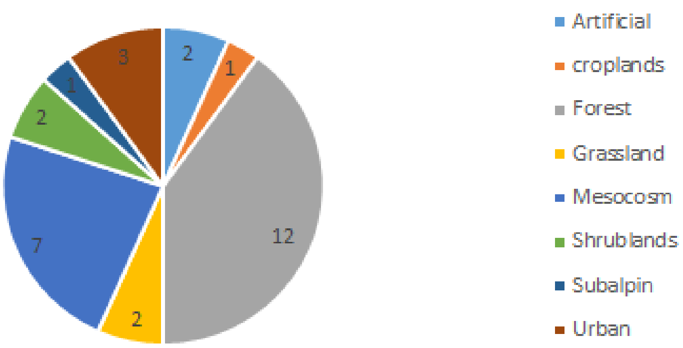


Figure 3 : Type of ponds in ponds studies

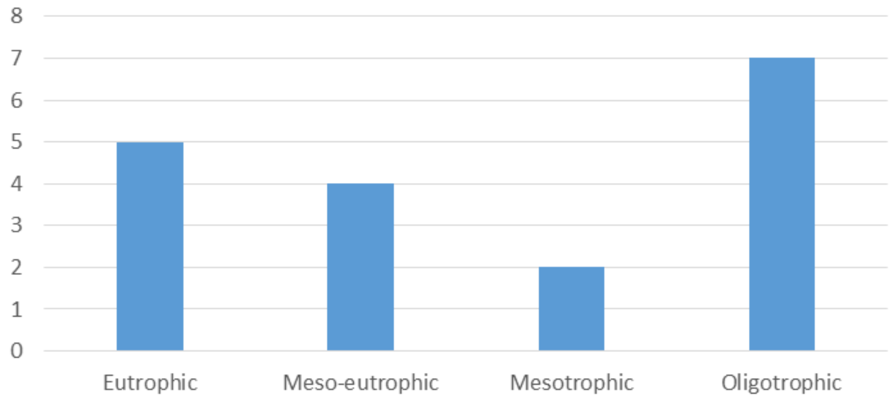


Figure 4 : Number of ponds studies by trophic system

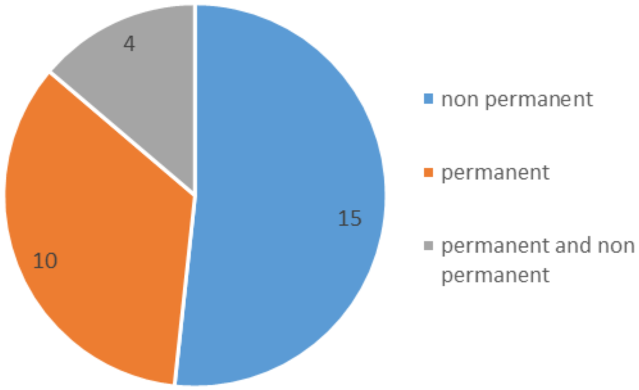


Figure 5 : Number of ponds studies by hydrological system

About the characteristics of the ponds studied, in Figure 3 several selected research papers focused on forest ponds (12 articles), and a large proportion of articles have chosen mesocosms, where conditions are easy to change (7 articles). Finally, there is a large number of articles dealing with non-permanent pools (15 articles), rather oligotrophic (7 articles) in Figure 4 and Figure 5.

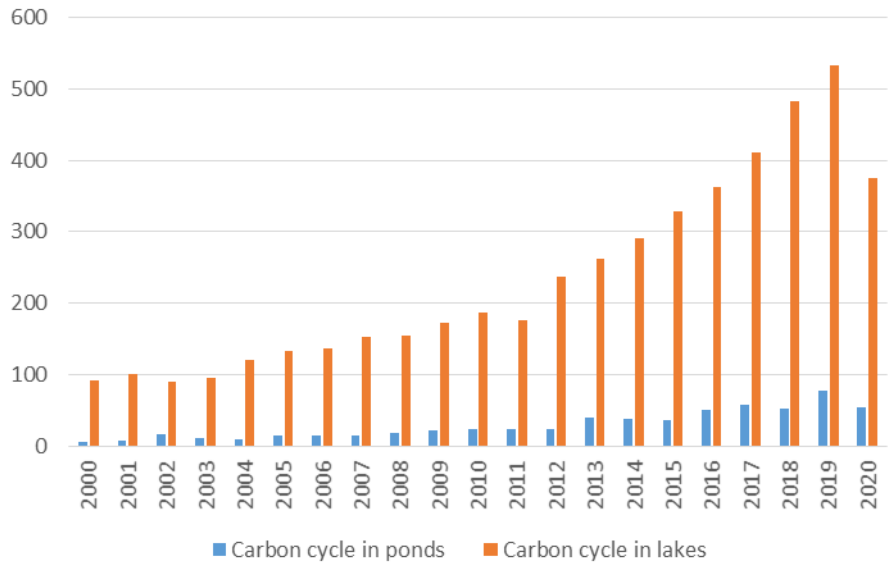


Figure 6 : Number of results on WOS by topic between 2000 and 2020

The figure above (Figure 6) aims to give a view about the carbon cycle of ponds in research in 20 years. According to the scientific database Web Of Science (WOS), the number of articles that deal with "carbon cycle in ponds" is increasing (614 articles between 2000 and 2020). However, compared to other aquatic systems such as lakes with 4 899 articles written about carbon cycle, ponds seem poorly studied.

3) The changing hydroperiod and its impact on the carbon cycle

a) The role and importance of the hydroperiod in the ponds functioning

First of all, it's important to define the important role of hydroperiod for the functioning of ponds.

Hydrology in small ponds has been affected on short and long-term by weather patterns and climate and is now really sensitive to climate change (Brooks, 2009). Indeed, the hydrology of wetlands is dominated by local meteorological conditions (Brooks, 2004). Ponds are fed by several means such as : groundwater, snow cover, runoff, etc. (Brooks, 2004). Being lentic systems often isolated from other aquatic systems, ponds are all the more sensitive to climate change as their feeding depends on these other systems (Brooks, 2009).

It is the water level in ponds that regulates the other factors, particularly the ecological functions (Brooks, 2000). The hydroperiod plays a role for the fauna. Indeed, the richness of biotic communities is influenced by the size of the ponds (Brooks, 2000) and the latter depends on the quantity of water available. The hydroperiod of ponds affects the richness and composition of vertebrate and invertebrate communities, the abundance of invertebrates, the biomass and production, the predators size, the diversity and also the reproduction of invertebrates and amphibians (Brooks, 2000). Indeed, macroinvertebrate richness and abundance are better when ponds are permanent. Also, the longer the hydroperiod, the greater the diversity (Brooks, 2000) (Figure 7). Concerning predation, studies have shown that it depends on the length of the hydroperiod, the longer the hydroperiod, the more predation increases (Schneider and Frost, 1996). The hydrology of wetlands and more particularly ponds plays a role in the productivity of settlements (Brooks, 2009). Moreover, the hydrological connection between the different aquatic systems participates on the one hand in the water supply and on the other hand in not isolating ponds from other lentic systems (Brooks, 2009). Indeed, the diversity of accessible breeding ponds guarantees genetic exchanges (Gamble et al., 2007).

Second, the hydroperiod affects the rate of degradation of litter and organic matter (Brooks, 2009). Indeed, the hydroperiod causes fluctuations that provoke drought-humidity cycles that modify microbial activity and consequently the decomposition of organic matter (Hervé et al., 2019). The decomposition rate depends on the water level and in particular, decomposition rates are higher in flooded areas than in non-flooded areas because soil humidification leads to increase microbial activity (Hervé et al., 2019; Hervé et al., 2020). But, on this point, there is no firm conclusion because, depending on the rate of humidification, the rate of decomposition still varies (Hervé et al., 2019). The rate of decomposition of organic matter also depends on the chemical quality of the organic matter and therefore on the plant species present (Hervé et al., 2020). These can vary according to the hydroperiod, as can the type and size of decomposers. For example, the presence of sphagnum moss reduces the rate of decomposition of organic matter (Hervé et al., 2020).

Finally, ponds are impacted by any changes in their hydrology (Hervé et al., 2020). The hydroperiod is the most important abiotic factor in ponds (Brooks, 2004). Indeed, with periods of drought and rehumidification, the biological, physico-chemical, etc. parameters of ponds are modified and this also has an impact on carbon storage (Brooks, 2009).

b) Impact on ponds communities : drivers of carbon cycle

Because of their small size, ponds are aquatic systems that are sensitive to large variations in hydroperiods (Calhoun et al., 2017). The first elements to be impacted are the actors of the carbon cycle : producers, consumers and decomposers of organic matter. They are the ones who allow the entry of carbon in the form of allochthonous or autochthonous organic matter (Hervé et al., 2018).

First of all, it appears that in the long term, changes in hydroperiod such as greater evaporation and more episodic rainfall events could lead to changes in the fauna of ponds (Brooks, 2009). Two taxa in particular : amphibians and invertebrates. In fact, prolonged drought increases the distance between potential breeding sites for amphibians, thus impacting the genetic diversity of populations (Brooks, 2005). Invertebrates, particularly the adaptation of macroinvertebrates in their life cycle, behaviour and morphology to the hydrological changes in permanent or temporary ponds, is sometimes so important that some authors fear a negative impact on the richness, abundance or productivity of populations face to more violent or temporally staggered hydrological events (Brooks, 2009).

Secondly, it seems that the water level and the soil moisture content of ponds, influence the microdistribution and the presence or absence of plant species (Bauder, 2005). Bauder explains that climate change modifies the hydrology of ponds involving a change in distribution and interaction between species, leading to a loss of structural diversity of habitats. Moreover, such a disturbance could favour certain species to the detriment of others. Finally, it appears that the hydroperiod of ponds may cause fluctuations in the metabolism of primary producers (Hornbach et al., 2017). Indeed, in their experiment, Hornbach chose a permanent pond and an ephemeral pond, and found differences in primary production and respiration. These processes were more important in the ephemeral pond (8.8 versus 5.0 mg O_2/L/day for primary production and -48.0 versus -38.9 mg O_2/L/day for respiration) (Figure 7). It could therefore be assumed that an increase in the transformation of permanent ponds into intermittent ponds would contribute to an increase in the metabolism of primary producers.

Finally, it is important to note that the presence of plants in ponds also affects microbial processes, including denitrification (Gutknecht et al., 2006) and decomposition (Hervé et al., 2019). In Hervé's article, the decomposition rate is lower in the presence of molinia and sphagnum mosses than sphagnum moss alone. It appears that the composition of the vegetation is important because it also influences the quantity and quality of the litter. Thus, a change in plant diversity due to a disturbed hydroperiod could also impact microorganisms in ponds.

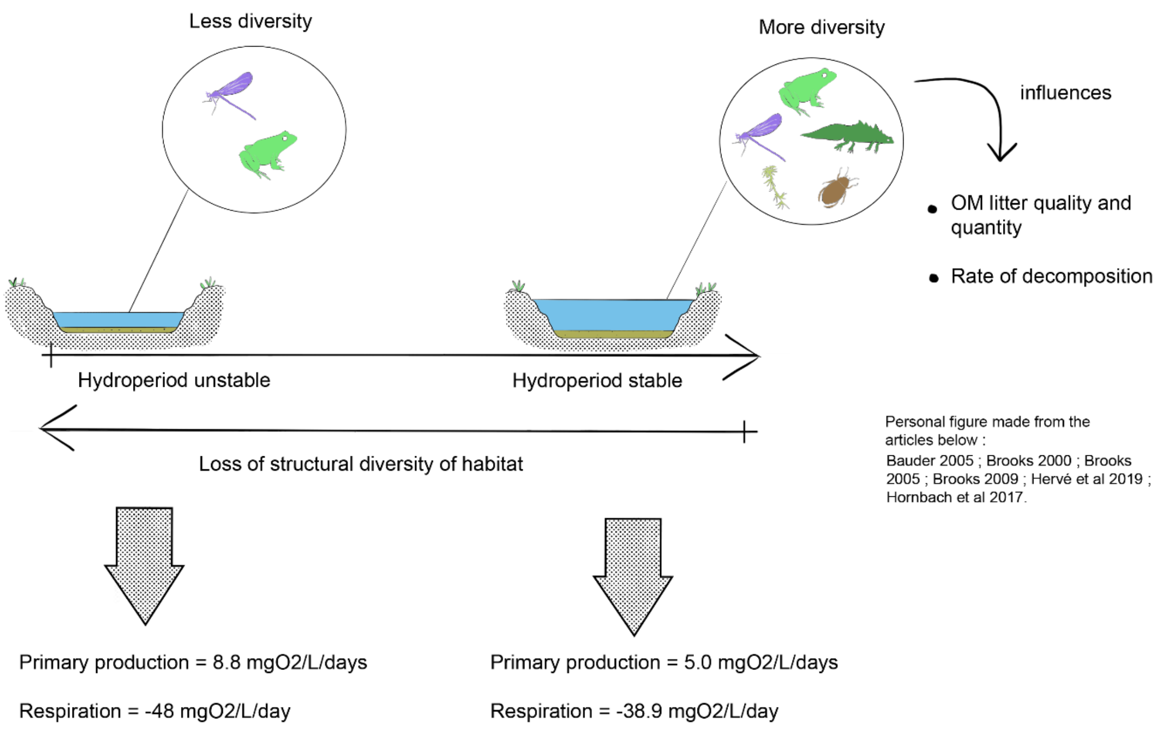


Figure 7 : Role and importance of the hydroperiod and its impact on ponds communities

c) Impact on pond decomposition processes and carbon fluxes

Wetlands and ponds more precisely, are places where microbial activity is very important in the sediments. As "biogeochemical hotspots" (Capps et al., 2014), microorganisms but also detritus feeders and the quality of the litter (i.e the plant species) of ponds are the key elements of the decomposition process (Hervé et al., 2020 ; Handa et al., 2014).

The hydroperiod does influence this biogeochemical process. Indeed, Capps et al. (2014) have observed that the degree of flooding influences both the decomposition of dead leaves but also the extracellular enzymatic activity. Thus, according to their observations, a longer hydroperiod increases the decomposition process, indeed the mass loss for the ponds with a longer hydroperiod was around 45 or 44 % against 38% for the intermittent pond.

In that respect, in conditions where the hydroperiod is disturbed with an increase of extreme drought and flood events, the hydrology of these small aquatic systems could suffer significant impacts. This is the case with the ponds studied by DelVecchia et al. (2019), which observes differences in atmospheric carbon flux between permanent ponds (246.0 ± 47.21 kg m−2), semi-permanent ponds (178.4 ± 11.0 kg m−2) and temporary ponds (674.1 ± 99.4 kg m−2) (Figure 8). Indeed, the latter having a lower water column, become more sensitive to changes that may occur, even within a day.

For example, reduced precipitation and excessive evaporation lowering water levels affect ponds, leading to increased methane emissions (Holgerson, 2015). In a subarctic climate, Laurion et al. (2010) also found that the thawing of ponds caused by global warming causes mineralization of accumulated organic matter as carbon dioxide and methane. With rivers and intermittent ponds, Datry et al. (2018) and Hervé et al. (2019) found that changing the

moisture content of plant litter causes intense microbial activity that increases the mineralization of organic carbon. In Datry's article, CO_2 emissions from intermittent rivers rewetted could reach 13.7 g CO_2 m−2 day−1 (Datry et al., 2018). In Hervé's experiments with mesocosms, mean decomposition rates reached 1.27% for the wet/dry treatment vs 1.06% for wet treatment and 1.19% for the wet/dry/rewet treatment (Hervé et al., 2019) (Figure 8). Several other studies observed a significant increase of CO_2 emissions when the sediments were exposed to the air and followed up by a period of desiccation and rewetting (Martinsen et al., 2019 ; Catalán et al., 2014 ; Gilbert et al., 2017 ; Fromin et al., 2010). Some of these authors even observed an increase in emissions when the wet sediments were vegetalized (Catalán et al., 2014 ; Gilbert et al., 2017), facilitating the way of carbon into the atmosphere probably. Finally, it appears according to Fromin that even the location of the microorganisms in the pond sediments affects their resilience after these drought periods. The resilience of microbial organisms to drought is greater if these organisms are located in sediments next to the edge of the ponds.

However, according to DelVecchia et al. (2019), microbial organisms, alone, do not explain this increase of carbon influx into the atmosphere. Even if hydroperiod changes lead to unfavorable conditions for microbial activity (aerobic conditions, reduced inputs and accumulation of OM), DelVecchia explains that detritus feeders also could have an important effect on carbon influx and should not be excluded. However, their relative effect on CO_2 emission rates compared to microbial decomposers is still poorly known in shallow lentic habitats. Moreover, the importance of abiotic elements such as geology, should not be dismissed as well. In his review, Marcé et al. (2019) evokes one of their studies in which carbonate-rich regions would be implicated in CO_2 emissions, explained by precipitation and dissolution reactions which seem to continue even after a dry period.

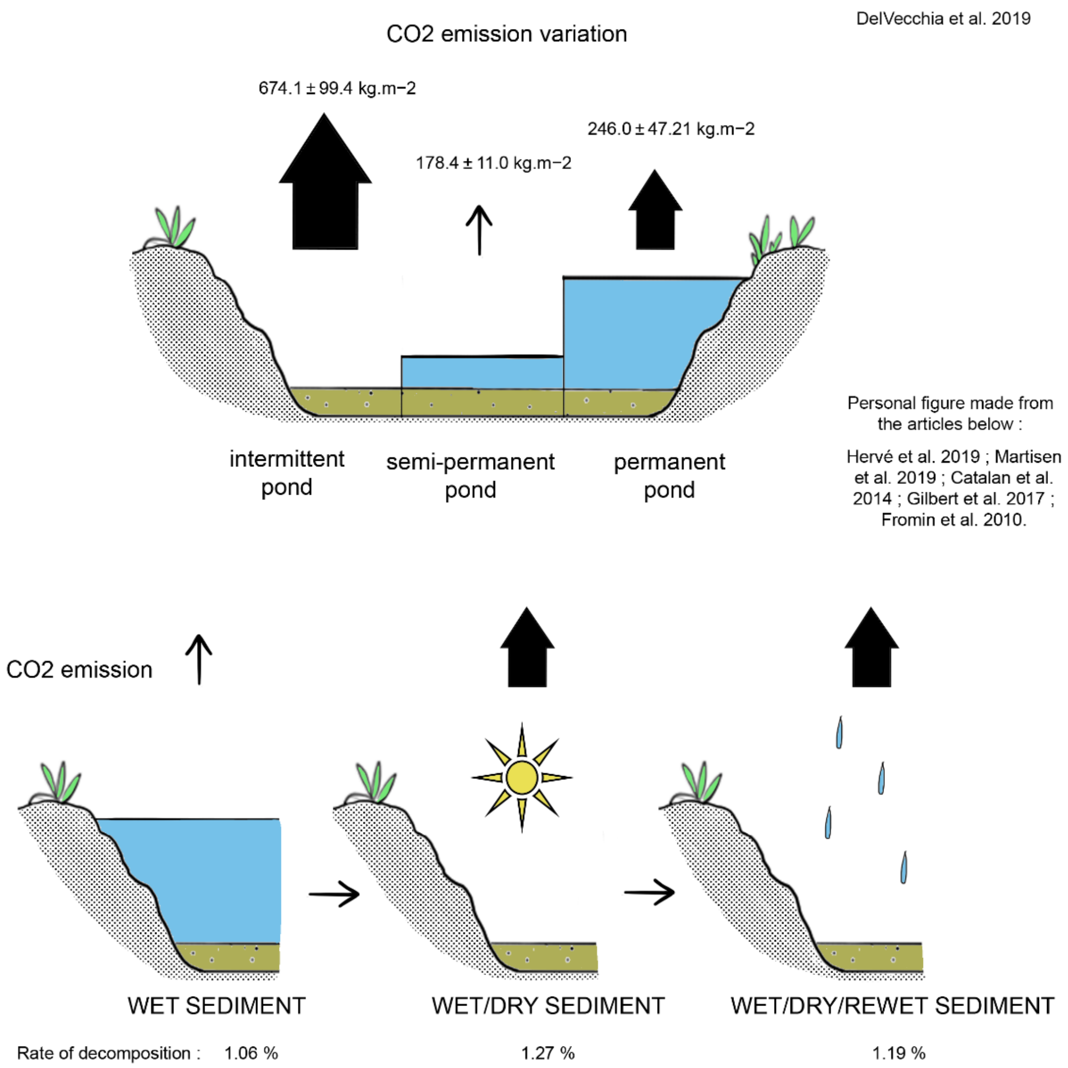


Figure 8 : Impact of hydroperiod on pond decomposition processes and carbon fluxes

4) The changing air and water temperature and its impact on the carbon cycle

a) The impact of heat on carbon cycle processes of ponds

Global warming of the atmosphere and water is the consequence of the increase of solar activity and greenhouse effect since the middle of the 19th century. Temperature appears to be an important factor which can impact pond processes.

For example Ali et al. (2016), studied ponds in semi-arid regions in India. They found that after simulating an increase of 2.8°C in the air (from 1.5 to 4.3°C), the water temperature in the ponds increased by 2.4°C (1.3 to 3.7°C). The elevation of air temperature has many cascading consequences on ponds chemistry. Thus, the rise of air temperature causes an increase of evaporation (17.2% on average) lowering the hydroperiod which decreases between 3 to 26 days, and the saturated dissolved oxygen which decreases between 2.2-6.5% (Ali et al., 2016). According to Hornbach et al. (2017), the rise of water temperature has direct consequences on the metabolism of ponds whatever the type of pond (forest pond or prarian pond in this

case). In all ponds, respiration and biomass of phytoplankton increases during the summer period.
Finally, temperature seems to have a significant effect on the structure and function of the food web which is one of the possible inputs of organic matter into ponds (Shurin et al., 2012). In the experiments, Shurin has shown that increasing water temperature by 3°C can have many direct and indirect effects. Contrary to Hornbach et al. (2017), the rise of temperature seems unfavourable for autotrophic organisms such as phytoplankton and periphyton (their biomass was reduced, while the biomass of benthic consumers increased). Moreover with predation, the rise of temperature seems to amplify the top-down effect of fish on phytoplankton (Figure 9), thus demonstrating the complexity of cascade effects on food web structure.

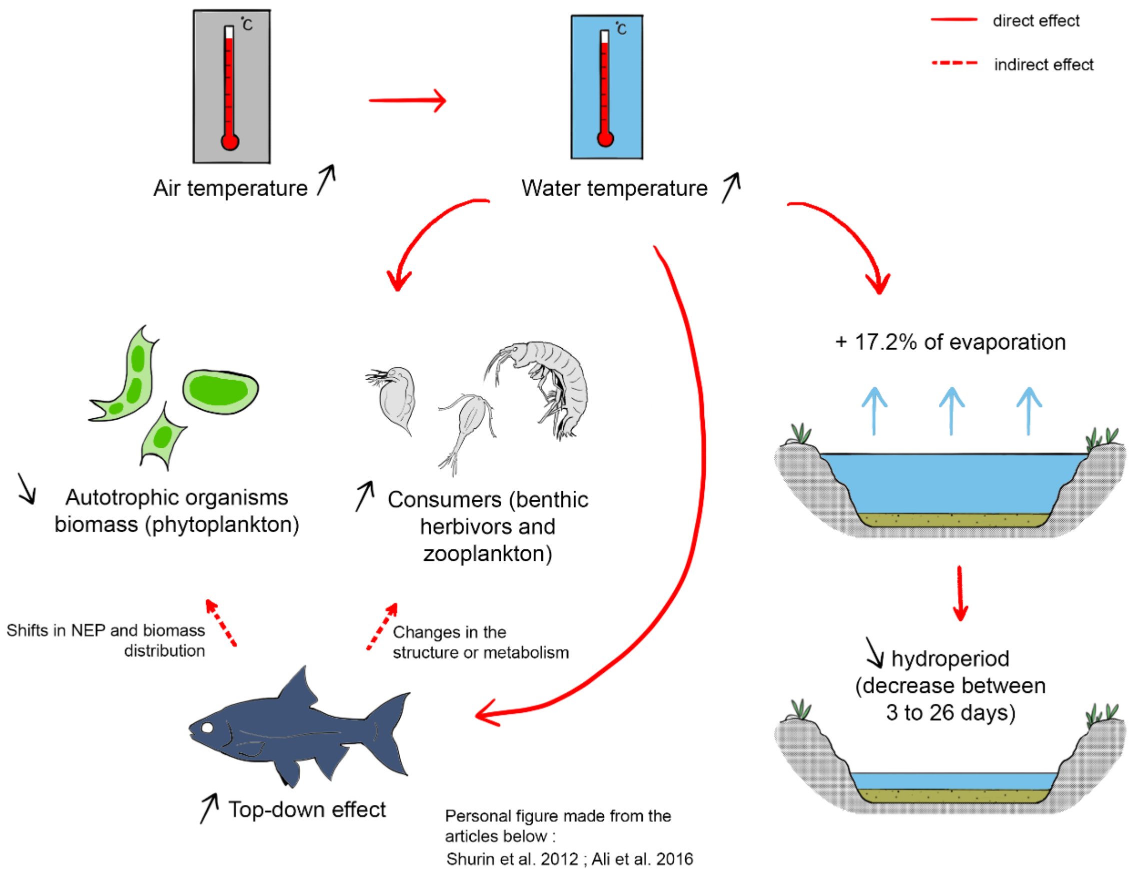


Figure 9 : Impact of heat on differents processus in ponds

b) Rising temperature creates favorable conditions for carbon emissions

As we have already seen, ponds are systems where carbon fluxes are important. We find outgoing CO_2 fluxes, which are more important during the night because this is when respiration for OM decomposers takes place (Natchimuthu et al., 2014). CO_2 fluxes are therefore dependent on primary production and respiration but also on the season (Natchimuthu et al., 2014). Then there are the CH_4 fluxes which are more important during the day than at night (Natchimuthu et al., 2014).

According to DelSontro et al. (2016), there is a link between water temperature and carbon fluxes. This link is more important when the environment is eutrophic. Indeed, the intake of

OM and the implementation of anoxic conditions are favourable to methanogenesis (DelSontro et al., 2016). The latter being dependent on temperature, it is very important in ponds because these are environments with a low water column which quickly leads to higher surface temperatures (Natchimuthu et al., 2014). In addition, as the hydrostatic pressure is low, it facilitates ebullition and thus CH_4 fluxes (Natchimuthu et al., 2014). We can thus underline the positive correlation between CH_4 fluxes and heat (Natchimuthu et al., 2014). Moreover, CH_4 fluxes are particularly related to sediment temperature (DelSontro et al., 2016). With climate change, we have seen that there are changes in precipitation regime. As precipitation are more intense, they may facilitate the transport of CH_4 from sediments to the atmosphere and reduce the methane oxidation time (Natchimuthu et al., 2014). DelSontro showed that ebullition fluxes contribute to 56% of CH_4 emissions in ponds, which is the major mode of transfer of CH_4 to the atmosphere (Natchimuthu et al., 2014) (Figure 10). It is also important to note that ebullition is more important in ponds (twice as much) than in lakes (DelSontro et al., 2016). According to Yvon-Durocher, long-term warming appears to alter the seasonality of CH_4 and CO_2 emissions (Yvon-Durocher et al., 2017). Indeed, his study showed a CO_2 emission peak in october when ponds are normally always CO_2 sinks, and a CO_2 absorption peak in june instead of july coinciding with the CH_4 emission peak (Figure 11). With increasing temperatures, there is an increase in CH_4 and CO_2 emissions and a decrease in CO_2 storage in ponds (Yvon-Durocher et al., 2017).

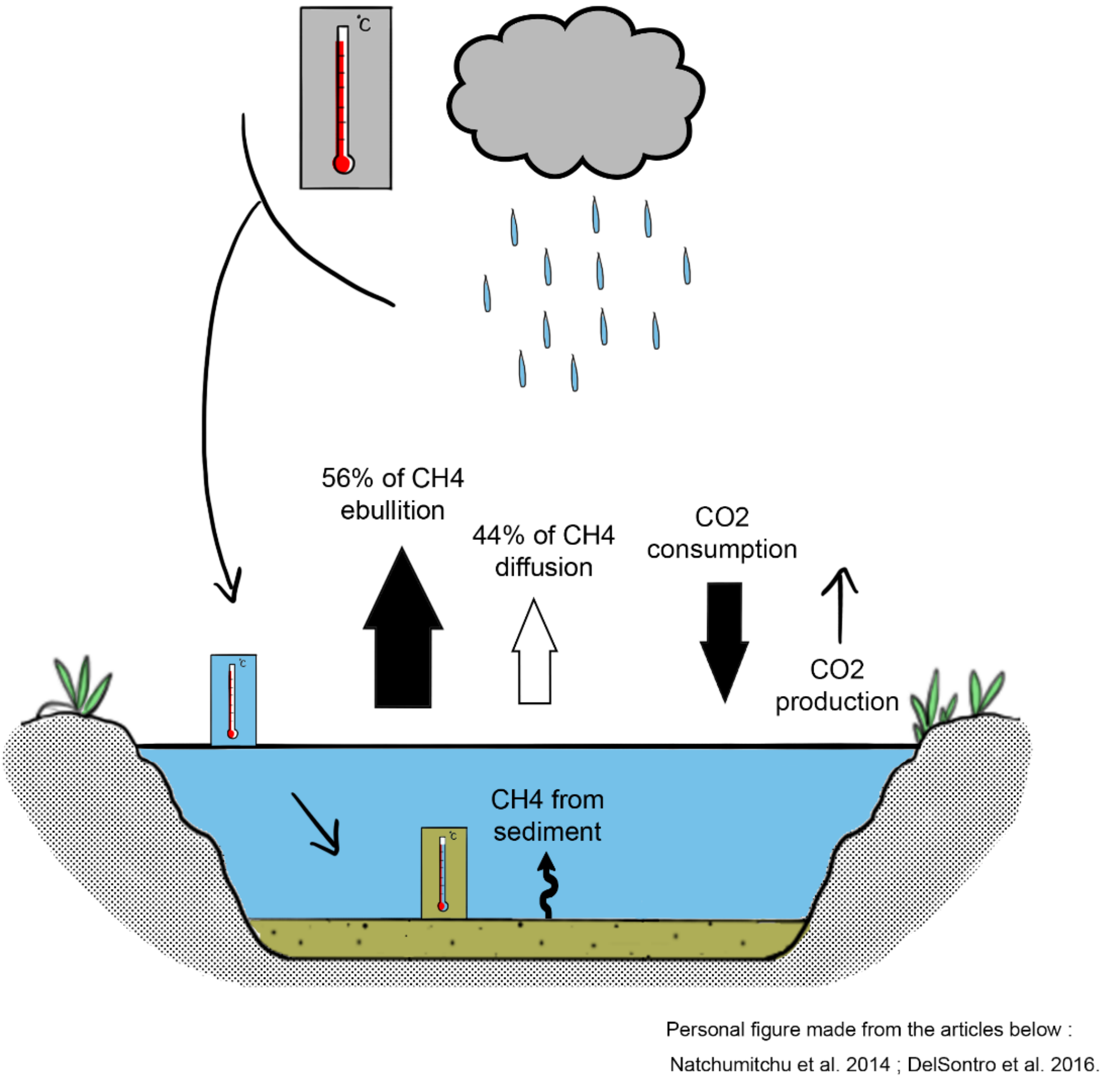


Figure 10 : Impact of temperature and weather on methane fluxes

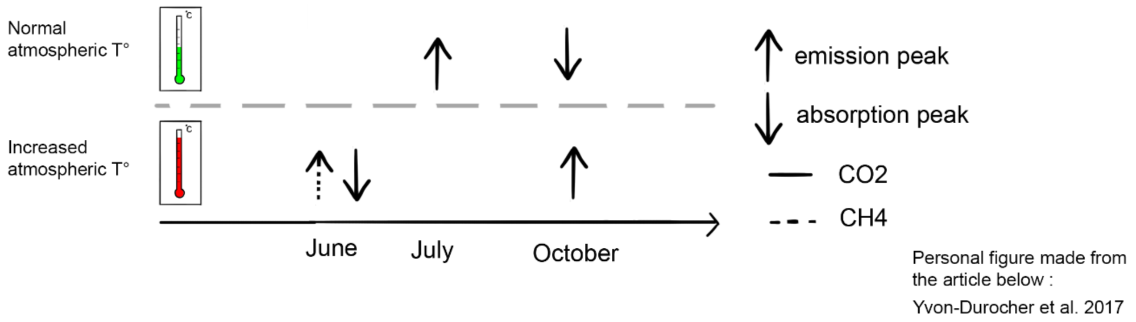


Figure 11 : Seasonality shift of carbon fluxes

Then, when temperatures increase, as for example with a 3°C warming of water, there are fewer primary producers and therefore more CO_2 efflux by organisms (Atwood et al., 2015). According to Yvon-Durocher, respiration and methanogenesis respond more strongly to temperature change than photosynthesis, but less CO_2 storage is observed (Yvon-Durocher et al., 2017). Indeed, a 1.15-fold increase in the respiration/primary production ratio has been shown, indicating a decrease in carbon sequestration. In addition, in 2013 the net absorption of CO_2 by ponds decreased by 50%. With the warming of water and subsequent eutrophication, we are seeing the extinction of some species (especially predators) and a change in the interactions between them (Atwood et al., 2015). Indeed, the warming of the air and then of the water has a negative effect on trophic cascades, herbivores consume more and there is a change in primary producers : a change in phytoplankton towards organisms that are more tolerant to stress but less productive (Figure 12). Moreover, the proliferation of primary producers caused by eutrophication and trophic cascades could only improve long-term carbon storage if plant matter escaped mineralization, which would allow the return of carbon and other elements to an inorganic form and thus usable again by plants (Atwood et al., 2015). For this, plant matter would have to be buried in the sediment, but we have seen earlier that higher water temperatures increase metabolism and mineralization rates (Atwood et al., 2015).

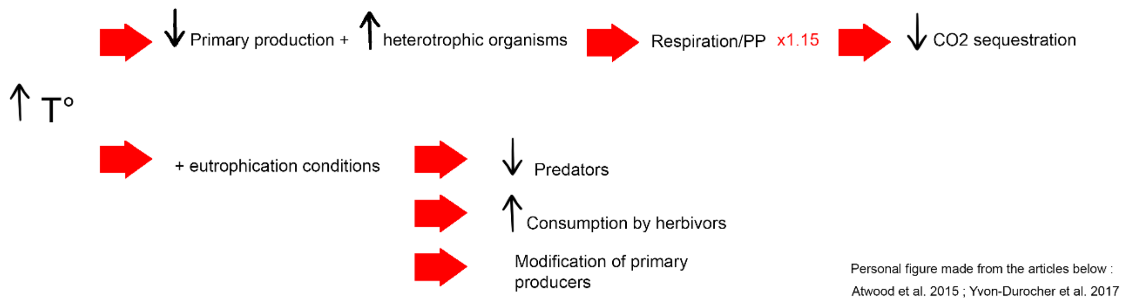


Figure 12 : Impact of temperature on organisms in ponds

Finally, the increase in temperature caused by climate change leads to long-term changes in the structure and functioning of ponds and this leads to a modification of the carbon cycle (Yvon-Durocher et al., 2017). That is why it is interesting to study in more detail the link between ponds and the carbon cycle, that is to say how climate change is affecting the carbon cycle in ponds, and how they react to the increase in greenhouse gas emissions into the atmosphere.

5) The impact of increasing atmospheric CO_2 on carbon cycle in ponds

The aim of this part is to take stock of current knowledge on the rate of carbon released into the atmosphere by small ponds and then to find out where we are in the research on the question : How does the increase of CO_2 in the atmosphere modify the carbon cycle in ponds ?

a) Ponds contribute to the increase of atmospheric carbon

First of all, we can address the case of thaw ponds, located in high latitudes. Global warming leads to a melting of the permafrost which induces the filling of these thaw ponds often rich in OM which will be mineralised and transferred to the atmosphere in the form of CO_2 and CH_4 (Laurion et al., 2010). The carbon stored in the soils is thus released into the atmosphere in the form of CO_2 and CH_4. It is indeed during the thaw cycle that decomposing microorganisms are most active. However, despite their significant contribution, thaw ponds are not taken into account in atmospheric carbon budgets. More detailed studies on them would certainly be needed to learn more about carbon escape rates in relation to global warming (Laurion et al., 2010) but also on the stocks of organic matter in soils (McGuire et al., 2009).

More generally, small ponds of lower latitudes account for a high percentage of CO_2 emissions compared to their size and it is for this reason that understanding the carbon fluxes in these systems is essential to adjust the current global carbon budget, especially as climate change is affecting the hydrology of ponds (DelVecchia et al., 2019). For example, according to Gilbert et al. (2017), the drier the ponds get, the more they tend to switch from carbon sinks to carbon emitters (Figure 13).

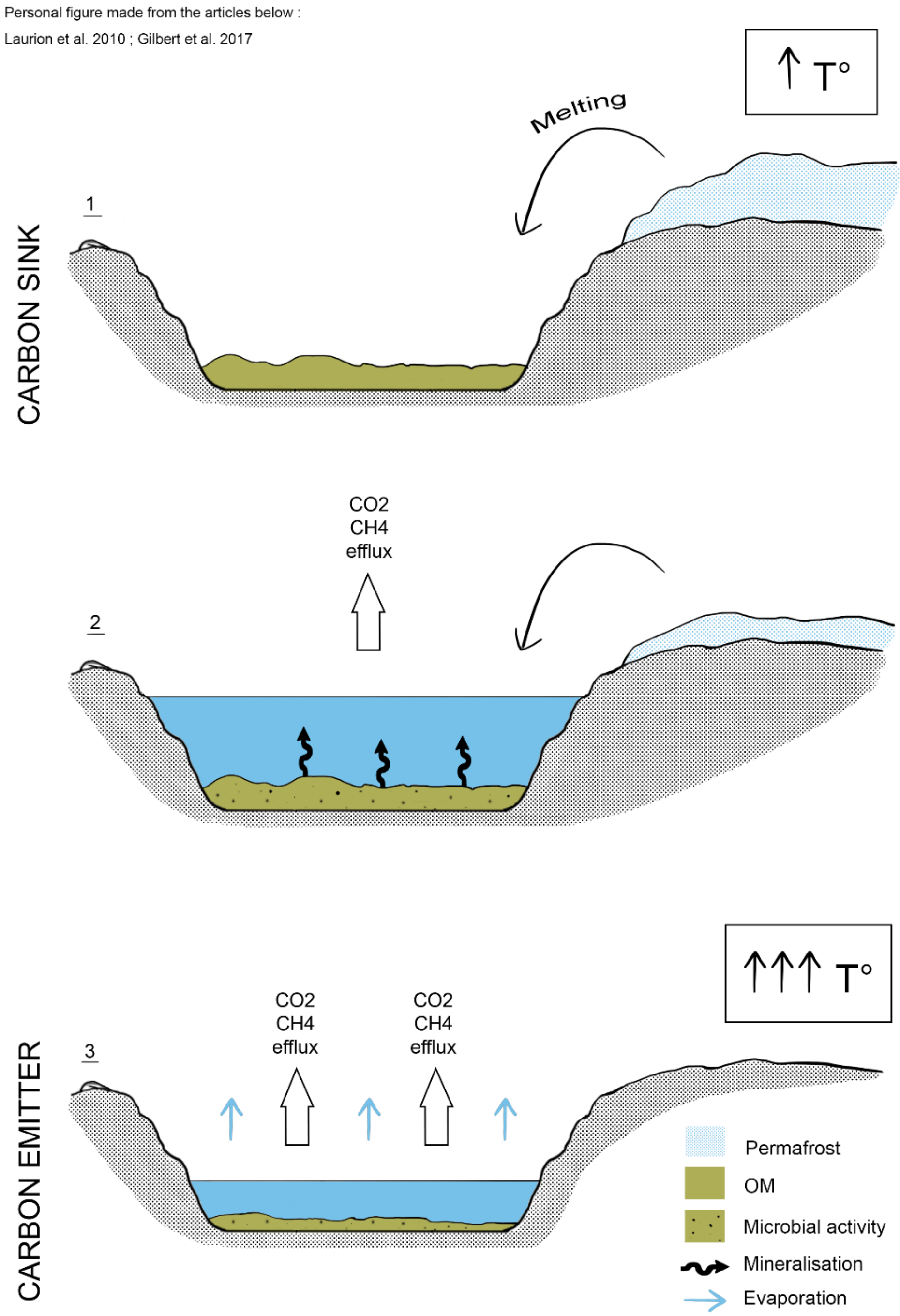


Figure 13 : Impact of carbon in thaw ponds on carbon fluxes to the atmosphere

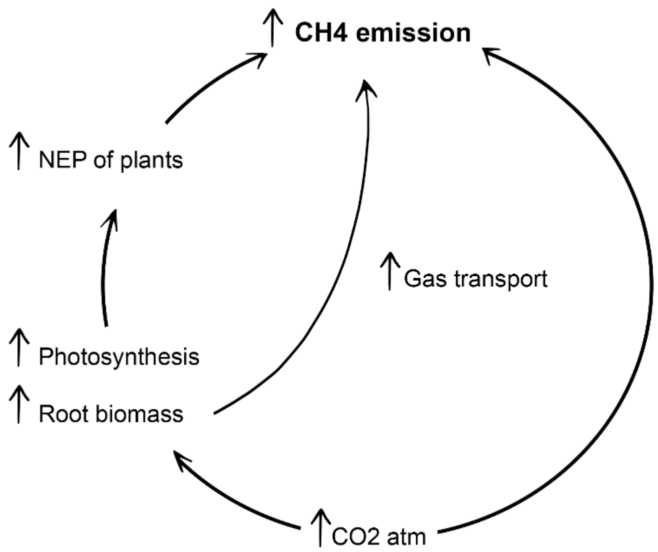
It has been shown by Bastviken et al. (2011) that continental freshwater contributes 103 teragrams/year of CH_4 (= 0.65 petagrams of C) and represents 25% of terrestrial carbon sinks. It would therefore be interesting to determine more specifically the contribution of ponds in these figures. It is also important to note that between 1750 and 2014 atmospheric methane concentrations increased by 150%, from around 850 ppb / year to around 1750 ppb / year (Pachauri et al., 2015).

According to Holgerson and Raymond (2016), very small ponds are responsible for 15.1% of CO_2 emissions and 40.6% of the diffusion of CH_4 to the atmosphere. Moreover, the CO_2/ CH_4 ratio of emissions increases more at the surface of ponds (105) than at the surface of lakes (19). This ratio clearly reflects the importance of ponds in the carbon cycle and even more so for CO_2.

So far, we have mainly seen that climate change is causing disruptions in the pond cycle. However, it seems that changes are taking place both in the functioning of ponds and in the atmosphere, causing an infinite cycle. Indeed, changes in the functioning of ponds then induce a change in the CO_2 and CH_4 content of the atmosphere.
Consider the study by Whiting and Chanton (1993) which predicts an increase in CH_4 emissions from wetlands due to several factors :

- The increase in the CO_2 content in the atmosphere,
- Stimulation of microbial activity in soils,
- Stimulation of primary production.

According to Whiting and Chanton (1993), one of the factors controlling CH_4 emissions is therefore the net primary production of plants in the environment. In addition, the increase in atmospheric CO_2 increases photosynthesis and root biomass, thus providing more substrate for CH_4 production (Liu et al., 2016)(Figure 14).
After this observation, it seems interesting to study in more detail the role of plants in the carbon cycle.



Personal figure made from the articles below :
Whiting and Chanton 1993 ; Liu et al., 2016

Figure 14 : Carbon cycle in ponds related to increasing atmospheric CO_2

b) Role of plants in CO_2 over concentrated atmosphere

For plants, CO_2 is known as a limiting factor. It appears that plants performing photosynthesis, especially C3 plants, reach their photosynthetic optimum into an atmosphere with a CO_2 concentration equal to 1000 ppm whereas it is normally around 335 ppm (Lemon, 2019). Increasing atmospheric CO_2 would therefore be an advantage for plants. **But what about the aquatic plants found in ponds ?** In the next articles, we hypothesize that the role of plants could be the same in ponds, even if authors did not mention specifically these aquatic systems.

Initially, it seems that the elevation of CO_2 has a positive effect on emergent aquatic plants such as *Azolla filiculoides* (Van Kempen et al., 2016). Indeed, Van Kempen observed in this species a significant increased growth under 1600 ppm of CO_2. Indeed, especially in spring, the biomass of *Azolla filiculoides* was multiplied by 2.5 compared to those placed under 400 ppm of CO_2. In addition, they noticed a decrease in the concentration of phosphorus and nitrogen nutrients in spring and fall under high CO_2, but also an accumulation of starch during summer. These observations show that with an atmosphere above 1000 ppm of CO_2, the demand for nutrients becomes more important for the growth of *Azolla filiculoides*, which store more synthesized carbon (Figure 15).

However, in the experiments of Hussner et al. (2019), the rise of atmospheric CO_2 has no real impact on submerged macrophytes such as Hydrocharitaceae species. Contrary to the *Azolla filiculoides*, Hydrocharitaceae are HCO3- users, so they seem less affected by the rise of atmospheric CO_2. Only the C/N ratio seems to increase significantly into the leaves (Figure 15).

The reaction of aquatic plants into ponds under high atmospheric CO_2 still seems to be poorly understood. Yet the presence of plants seems to alter the conditions of the environment to be a source or a sink. Under high CO_2, the process of carbon decomposition becomes significant whereas with aquatic plants such as *Eichhornia crassipes*, the process decreases (Shi et al., 2020). Indeed, *Eichhornia crassipes* appears to decrease the composition of bacterial communities responsible for CO_2 assimilation in eutrophic water, including photosynthetic bacteria and chemoautotrophic bacteria (the phylum Chloroflexi, orders Synechococcales, Rhodospirillales, and Oceanospirillales, and families Mycobacteriaceae, Roseiflexaceae, and Nitrosomonadaceae). Thus, in the presence of *Eichhornia crassipes* under CO_2 above 400 ppm, the system becomes a carbon sink (Figure 15).

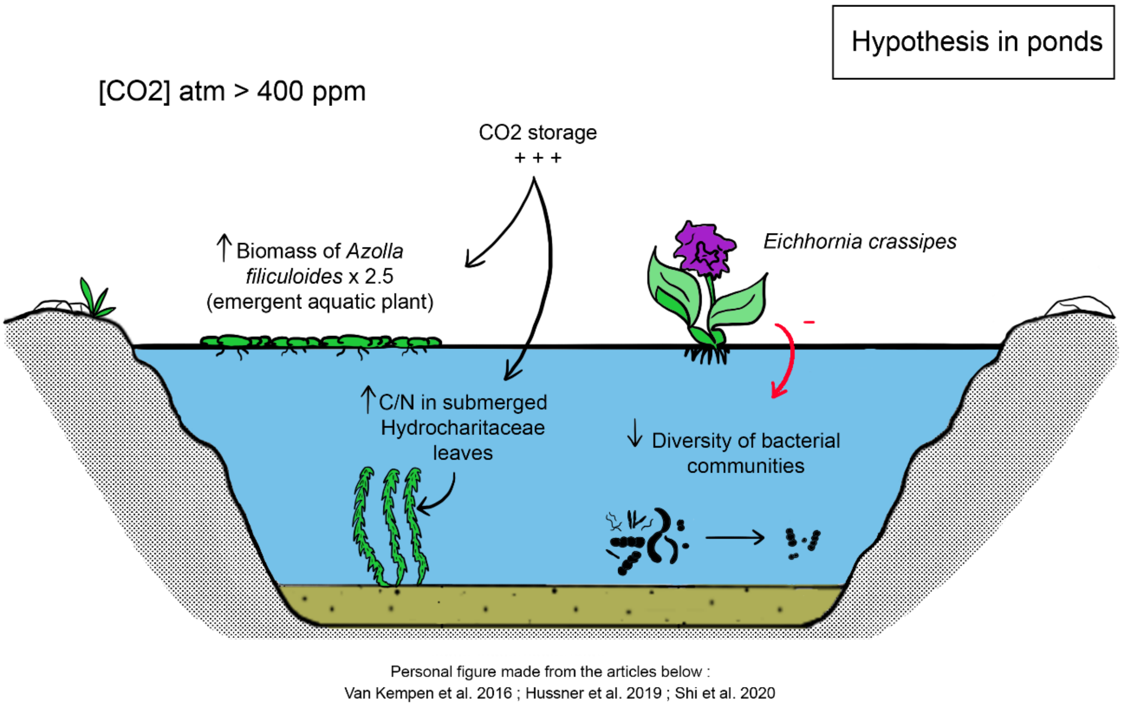


Figure 15 : Role of plants in ponds

Conclusion

Finally, this state of art about the impact of climate change on carbon cycle in ponds makes it possible to observe first, the impact of climate change on various parameters and in particular : the hydroperiod, the air temperature and then the water temperature, the CO_2 concentration in the atmosphere (Figure 16). These modifications then have consequences on ponds, which subsequently lead to changes in carbon cycle. Nevertheless, current knowledge of carbon cycle in ponds does not allow us to come to a clear conclusion that ponds will become carbon sources or sinks in the future.

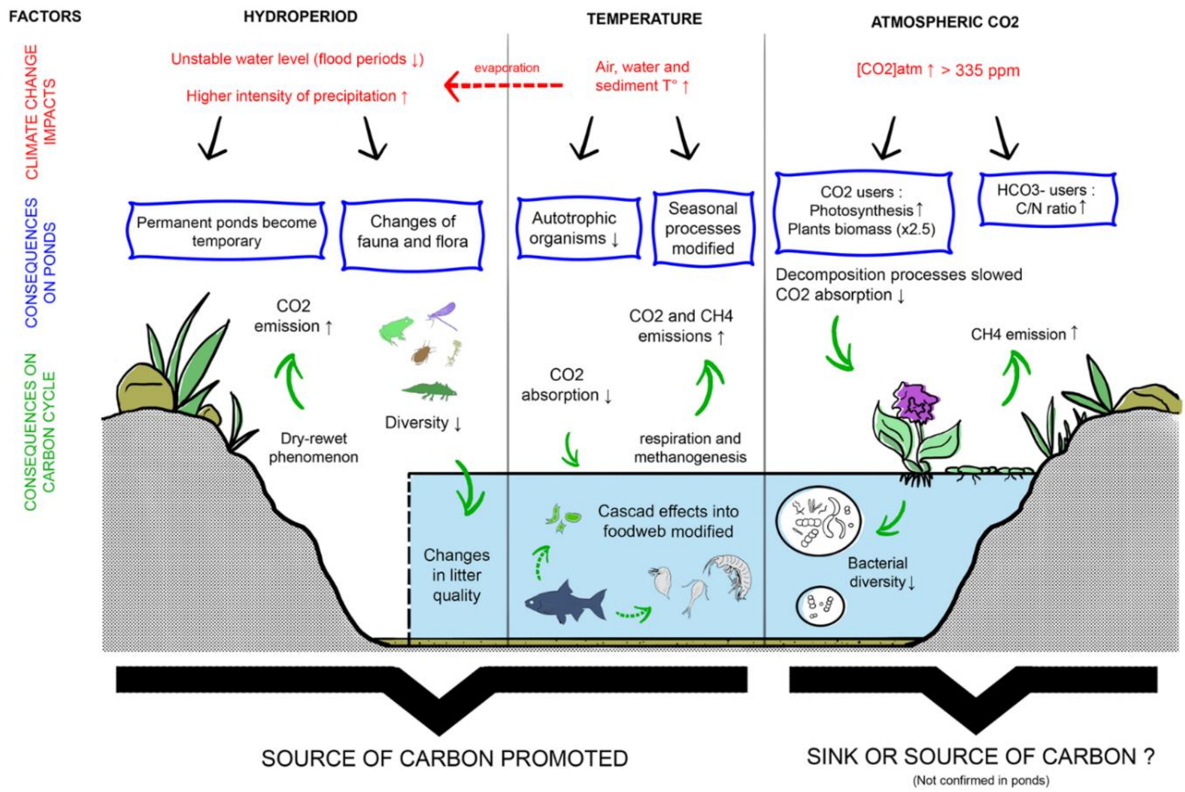


Figure 16 : Outline of the review (personal figure)

Until now, ponds in the polar regions have been little studied with regard to their production of greenhouse gases (Laurion et al., 2010). However, the thawing of permafrost has been identified as one of the 5 most vulnerable carbon reservoirs that can have important consequences on atmospheric carbon (Laurion et al., 2010). Indeed, thaw basins are found on carbon-rich soils. It would therefore seem judicious to study in more detail the impact of global warming on carbon fluxes in these sensitive regions. Similarly, studies are more often focused on two continents, European or American ponds (cf. Ponds bibliometric). However, it would be relevant to study ponds around the world, which respond to different characteristics of their environment to better understand their functioning and then to better preserve them.

Many factors favour the accumulation of greenhouse gases in ponds, such as the fact that there is a difference between the nature of the available OM and the microbial communities present (Laurion et al., 2010). According to Handa et al. (2014), it is important to take into account the characteristics of the plants and decomposer communities present in the ponds in order to predict the carbon cycle. That is why pond restoration projects must be based on

this to have functional environments that store carbon as much as possible. Furthermore, according to McGuire et al. (2009), with global warming, models predict a significant increase of CH_4 into the atmosphere as well as higher CO_2 released, linked to the acceleration of OM decomposition and an of forest fires. However, it is necessary to continue studies to understand how the carbon cycle in ponds will evolve in the context of global warming in relation to the processes that tend to increase CO_2 absorption and those that tend to increase its release.

Also, few studies focus on detritivorous organisms and microbial decomposers in ponds (DelVecchia et al., 2019). However, these animals are responsible for a large CO_2 flux in ponds and their survival also depends on the hydroperiod (DelVecchia et al., 2019). For this reason, it would be interesting to carry out studies on detritivorous organisms and more particularly on their evolution with changes in the hydroperiod to know better the impact on carbon fluxes in ponds.

It should be noted that ponds have not been studied in all their complexity to have sufficient data. To overcome this lack of information, Marcé et al. (2019) propose a participatory data collection platforms. The objective is to rapidly identify data about wetland carbon emissions. Thanks to that, it is possible to cover a large area and involve many people. This kind of sampling initiative has been set up for the DryFlux project, where the aim is to improve knowledge about CO2 emissions in dry aquatic areas. In France, the SNPN (Société nationale de protection de la nature) launched "L'inventaire des mares d'Ile-de-France" in 2010, with the idea to make an inventory of ponds but also to raise awareness about them and promote them (Lhotelin et al., 2017). This project enabled more than 23 000 ponds to be mapped, more than 16 000 taxonomic data to be recorded and events about wetland preservation to be organised. The prospects for action in the future, are to continue this inventory of ponds and subsequently to carry out conservation actions of these environments. In addition, ponds are habitat for many species, particularly protected species such as Crested Triton or Tree Frog in France. As a result, not only these species but also their habitat are protected by regulations. For this reason, actions to identify the species present in the ponds are an important means of conserving them.

Ponds are not only under the threat of climate change, but they are also subject to other pressures : invasive species, changes of land use, inadequate regulations (ponds are hardly taken into account in protection measures) (Calhoun et al., 2017). That is why, following the studies already carried out and the observation that some ponds have been destroyed by changes in agricultural practices or by the artificialisation and urbanisation of natural environments, restoration work is being carried out on certain ponds and is being monitored (https://www.snpn.mares-idf.fr/presentation/presentation_menaces_et_protection.php).
Indeed, it has been shown that in wetlands with drainage, the carbon cycle is accelerated, which increases the release of CO_2 and CH_4 into the atmosphere and thus contributes to the increase in greenhouse gas emissions (Kayranli et al., 2010). In addition, in impacted wetlands, water quality is altered with an altered water level, which also plays a role in the carbon cycle by the fact that nutrients are released more quickly (Kayranli et al., 2010). Ponds, and more broadly temporary wetlands, are more difficult to protect as they represent an ephemeral resource (Calhoun et al., 2017).
According to Kayranli et al. (2010), vegetated wetlands can store 2 to 15 times more carbon than they can emit as CO_2 into the atmosphere. Moreover, plants respond positively to an increase of atmospheric CO_2 that we are facing with climate change. In the atmosphere we

have an average of 335 ppm of CO_2, but for plants the optimum level of CO_2 for photosynthesis is 1000 ppm (Foyer, 1984). For these reasons, it could be important to re-vegetate wetlands, to return the ponds to their characteristic as a carbon sink.
Secondly, artificial wetlands have a neutral or even cooling effect on the climate according to Kayranli et al. (2010). For this reason, it seems essential to deepen our knowledge on this subject to potentially take advantage of this cooling effect to protect wetlands and ponds that are still natural and sensitive to global warming.

Finally, the importance of ponds and their ecological and economic value have been put into practice in recent years, but research dealing with the evolution of ponds in relation to climate change still needs to be deepened. Nevertheless, conservation actions need to be carried out to preserve these wetlands. Different approaches are possible such as : educating, inventorying, protecting, developing in a sustainable way, restoring, or creating.

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Annexes

Tableau 1: Bibliometrics

Article	Year	Number of ponds	Study site location	Continent	Climate	Type of ponds	Surface (m^2)	Mean depth (m)	Perennial	Trophic system
Brooks	2000	5	Central Massachusetts (USA)	North America	Humid continental	Forest	250 - 600	0.18 - 1	yes and no	
Brooks	2004	4	Central Massachusetts (USA)	North America	Humid continental	Forest	<1000	0.5 - 1	no	
Pyke	2005	4	Central Valley of California (USA)	North America	Mediterranean				no	
Bauder	2005	10	California (USA)	North America	Mediterranean				no	
Magnusson et al	2006	4							no	
Brooks	2009		Northeastern United States	North America	Humid continental	Forest			no	
Fromin et al	2010	1	Camargue (France)	Europe	Mediterranean				no	
Laurion et al	2010	52	Nunavik and Nunavut (Canada)	North America	Subartic	Shrublands, forest		1 - 3		Meso-eutrophic
Shurin et al	2012	40	Vancouver (Canada)	North America	Marine west coast	Mesocosm			yes	
Natchimuthu et	2014	1	Linköping (Sweden)	Europe	Marine west	Urban	1 200	1.2	yes	
Catalán et al	2014	12	Balearic Islands (Western Mediterranean)	Europe	Mediterranean	Urban and forest	44 - 1945		no	
Capps et al	2014	3	Northeastern United States	North America	Humid continental	Forest			no	
Atwood et al	2015	40				Mesocosm	1.8	0.6	yes	Meso-eutrophic
Holgerson et al	2015	6	Connecticut (USA)	North America	Humid continental	Forest	300 - 800	< 1	no	Oligotrophic, Mesotrophic, Eutrophic
Ali et al	2016	1	Rajasthan (India)	Asia	Tropical wet	Artificial	4 700	2.75	no	
DelSontro et al	2016	10	Saguenay (Quebec)	North America	Humid continental	Forest	1 200 - 42 000	0.6 - 0.9	yes	Meso-eutrophic

Article	Year	Number of ponds	Study site location	Continent	Climate	Type of ponds	Surface (m^2)	Mean depth (m)	Perennial	Trophic system
Holgerson et al	2016	427							yes	Oligotrophic, Mesotrophic, Eutrophic
Van Kempen et al	2016		Nijmegen (Netherlands)	Europe	Marine west coast	Mesocosm		< 1	yes	
Hornbac et al	2017	2	Minnesota (USA)	North America	Humid continental	Forest, Grassland	12000 - 1 900	0.92 - 0.26	yes and no	Eutrophic
Yvon-Durocher et al	2017	20	East Stoke (UK)	Europe	Marine west coast	Mesocosm		0.5	yes	
Gilbert	2017	26	Northumberland (UK)	Europe	Marine west coast	Artificial	1	0.3	no	
Drzewicki et al	2018	1	Wrocław (Poland)	Europe	Marine west coast	Urban	33 000	3	yes	Eutrophic
Hervé et al	2018	40	Indre-et-Loire (France)	Europe	Marine west coast	Forest	200 - 2 000	0.25 - 1,25	no	Oligotrophic
Obrador et al	2018	10	Balearic Islands (Western Mediterranean)	Europe	Mediterranean	Forest, croplands, shrubland		1	no	Meso-eutrophic
Hervé et al	2019	7	Indre-et-Loire (France)	Europe	Marine west coast	Mesocosm		0.36	yes and no	Oligotrophic
Martinsen et al	2019	7	Öland (Sweden)	Europe	Marine west coast	Grassland			no	Oligotrophic
DelVecchia et al	2019	12	Central Colorado (USA)	North America	Alpine	Subalpin	81 - 5200	0.03 - 1.6	yes and no	
Hussner et al	2019	10	Eastern Cape (South Africa)	Africa	Humid subtropical	Mesocosm		< 1	yes	Oligotrophic
Hervé et al	2020	14	Indre-et-Loire (France)	Europe	Marine west coast	Forest	200 - 1000	0.8 - 2	no	Oligotrophic
Shi et al	2020	8	Jiangsu (China)	Asia	Humid subtropical	Mesocosm		< 1	yes	Eutrophic

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POLYTECH TOURS
Département
Aménagement et Environnement

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IMA
2020-2021

Titre : Impact des changements climatiques sur le cycle du carbone dans les mares de petite taille

Résumé :
Peu d'articles dans la recherche scientifique se penchent sur les mares. Or, malgré leur petite taille, elles représentent en surface des zones d'eau stagnantes très sous-estimées. De plus, elles présentent de nombreux enjeux et rendent des services écosystémiques majeurs comme : provision en eau et en nourriture, régulation de la quantité d'eau ou encore du taux de nutriments et support de la biodiversité. Ce n'est que depuis quelques années qu'il y a une réelle prise de conscience de l'intérêt des mares et de leur rôle dans notre écosystème.
Cependant, avec les changements climatiques auxquels nous faisons face, les mares qui sont des écosystèmes fragiles tendent à disparaître ou à subir des modifications de leur fonctionnement.
Les objectifs de cette review sont :
- d'analyser la bibliométrie des principales études liées au sujet et de présenter la tendance des études passées et présentes,
- d'analyser comment le changement climatique affecte les différents paramètres qui structurent les mares et quelles sont les implications sur les flux de carbone et les émissions de gaz à effet de serre,
- d'identifier les lacunes dans les connaissances actuelles sur les flux de carbone en relation avec le changement climatique dans les mares de petite taille.

Ce projet de fin d'études est associé à une opération de recherche, le projet BIOMAN.

Mots Clés : Mare, Cycle du carbone, Changement climatique, Dioxyde de carbone, Méthanogénèse, Flux, Ecosystème, Hydropériode, Température, Plantes, Review

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2020-2021

Title : Impact of climate change on the carbon cycle in small ponds

Abstract :
Few articles in scientific research focus on ponds. Yet, despite their small size, they represent very underestimated areas of stagnant water on the surface. Moreover, they present many challenges and provide major ecosystem services such as the provision of water and food, regulation of water quantity and nutrient levels and support for biodiversity. It is only in recent years that there has been a real awareness of the importance of ponds and their role in our ecosystem.
However, with climate change, ponds are vulnerable ecosystems which are tending to disappear or which are undergo changes in their functioning.
The objectives of this review are :
- to analyse the bibliometry of the main studies related to the subject and present the tendency of past and present studies,
- to analyse how climate change affects the different parameters structuring ponds and what are the implications for carbon fluxes and greenhouse gas emissions,
- to identify gaps in the current knowledge about carbon fluxes in relation to climate change in small ponds.

This end-of-study project is associated with a research operation, the BIOMAN project.

Key words : Pond, Carbon cycle, Climate change, Carbon dioxyde, Methanogenesis, Efflux, Ecosystem, Hydroperiod, Temperature, Plants, Review