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Possible future effects of large-scale algae cultivation for biofuels on coastal eutrophication in Europe

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HIGHLIGHTS

- Future trends in fertiliser use associated with biodiesel production from algae
- Part of waste will be transported by the rivers to the coastal waters
- Our scenarios are inspired by a publication in Science by Wijffels and Bardosa (2010)

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ABSTRACT

Biodiesel is increasingly considered as an alternative for fossil diesel. Biodiesel can be produced from rapeseed, palm, sunflower, soybean and algae. In this study, the consequences of large-scale production of biodiesel from micro-algae for eutrophication in four large European seas are analysed. To this end, scenarios for the year 2050 are analysed, assuming that in the 27 countries of the European Union fossil diesel will be replaced by biodiesel from algae. Estimates are made for the required fertiliser inputs to algae parks, and how this may increase concentrations of nitrogen and phosphorus in coastal waters, potentially leading to eutrophication. The Global *NEWS* (Nutrient Export from WaterSheds) model has been used to estimate the transport of nitrogen and phosphorus to the European coastal waters. The results indicate that the amount of nitrogen and phosphorus in the coastal waters may increase considerably in the future as a result of large-scale production of algae for the production of biodiesel, even in scenarios assuming effective waste water treatment and recycling of waste water in algae production. To ensure sustainable production of biodiesel from micro-algae, it is important to develop cultivation systems with low nutrient losses to the environment.

1. Introduction

1.1. Background

Biofuels are often mentioned as promising alternatives for fossil fuels. The first generation biofuels can be produced from, for instance, grains, sugar cane and vegetable oils. There are, however, concerns about replacing food crops by these first generation biofuels. The second generation of biofuel production is based on waste residues and makes use of abandoned land (Eisentraut, 2010). However, also the second generation biofuels can be unsustainable in case they compete with food crops for available land.

Lipids from micro-algae can be used to produce biodiesel. Likewise, biodiesel can be produced from lipids from rapeseed, soybean, sunflower and palm. Green micro-algae, such as the single-cell algae belonging to the genus *Chlorella*, can be grown commercially. The process of algae cultivation has been described elsewhere (Wolkers et al., 2011). The productivity per hectare of micro-algae is considerably higher than that of other energy crops. Biodiesel from algae can therefore be considered an example of a third generation biofuel (Ahmad et al., in press).

Biodiesel is considered environmental friendly because of low greenhouse gas emissions. Also biodiesel from algae has been suggested as a climate friendly alternative for fossil fuels in the future (Ahmad et al., in press), although several studies indicate that with current technologies the production of biodiesel from algae is not yet energy efficient (Reijnders, 2009). Others, however, argue that biodiesel may be the only renewable alternative for fossil diesel for heavy traffic (Mackay, 2010).

Production of algae is currently mainly taking place at the pilot scale. It is expected that full-scale production sites may be operational in Europe within the coming decades. Algae production usually takes place in so-called algae parks. Such parks may consist of open ponds

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or raceways, single-layer or horizontal tube reactors, three dimensional tube reactors and flat plate reactors. The open pond is an open system, while the other systems are all closed in the sense that there is no open contact with the environment.

Algae production may have environmental implications. Several life cycle assessments (LCAs) have been published, indicating that these environmental implications are largely associated the use of fertilisers, energy, and water (Brentner et al., 2011; Clarens et al., 2010; Lardon et al., 2009; Liu and Ma, 2009; Yang et al., 2011). Relatively high fertiliser inputs are needed during algae cultivation, resulting potentially high losses of nutrients such nitrogen (N) and phosphorus (P) to the environment, giving rise to eutrophication. Other LCA studies indicate that nutrient losses as a result of fertiliser use deserve particular attention because of the large amounts that are potentially lost to the environment (Clarens et al., 2010, 2011; Lardon et al., 2009; Yang et al., 2011).

This study focuses on the impact of land-based micro-algae production on aquatic systems. The study is a modelling study applying scenario analysis on the basis of hypothetical assumptions, and investigates the environmental consequences of our assumptions on micro-algae cultivation for biodiesel production in Europe. Algae parks require considerable inputs of nutrients, in particular N and P. These nutrients are only partly incorporated in algae tissue. The remainder is recycled, or leaving the system as waste or loss to the environment. Losses to the environment include gaseous losses such as dinitrogen (N_2), amonia (NH_3), nitrogen oxides (NO_x) and nitrous oxide (N_2O), and losses to aquatic systems. Recycling of nutrients is possible, but not yet current practice in operational algae production sites. Recycling can take place by collecting and re-use of the algae biomass after harvesting. The process of recycling is, however, not the subject of this study. The liquid waste streams from algae parks are generally treated as municipal sewage discharging to rivers. Thus part of the N and P used in algae production may be lost to the aquatic system.

Increased nutrient levels in streams and rivers may lead to eutrophication in fresh and marine waters (Diaz and Rosenberg, 2008; EEA, 2001; Seitzinger et al, 2010; Sutton et al., 2011). Eutrophication in surface waters may lead to harmful algae blooms which may be toxic for other organisms. In extreme cases aquatic eutrophication may lead to hypoxia. It thus poses a threat to biodiversity, fish stock, and recreation. The risk for coastal eutrophication is depending not only on N and P enrichment but also on the ratio of N or P to other elements (Billen and Garnier, 2007). Analyses for the coastal waters of the EU27 indicate that the nutrient availability in coastal waters is currently disturbed and a cause of severe eutrophication events (Sutton et al., 2011). In the future, however, this may change. Environmental and agricultural policies aim at a decrease in the export of N and P by rivers to coastal waters in Europe. Scenarios exploring future trends in Europe indeed indicate that the risk for coastal eutrophication may decrease in the future (Garnier et al., 2010; Seitzinger et al, 2010; Strokal and Kroeze, 2012). These scenarios, however, do not account for a possible increase in the production of micro-algae on land.

The purpose of this study is to analyse the potential consequences of large-scale land-based production of biodiesel from micro-algae in Europe for coastal eutrophication. The main focus is on N and P export by major rivers in the 27 countries of the European Union (EU27) to four large European seas: the North Sea, the Mediterranean Sea, the Black Sea and the Baltic Sea. The analysis is based on hypothetical scenarios for the year 2050 assuming that fossil diesel used in EU 27 countries will be replaced by biodiesel from algae.

1.2. Global NEWS

In this study the focus is on major rivers in the EU27 that discharge into the coastal waters of the Mediterranean Sea, the Baltic Sea, the Black Sea and the Atlantic Ocean. The analysis follows future export of N and P by these rivers with the Global *NEWS* (Nutrient Export from WaterSheds) model (Mayorga et al., 2010; Seitzinger et al, 2010; Seitzinger et al., 2005). The Global *NEWS* model has been used to analyse future trends in river export of nutrients based on the Millennium Ecosystem Assessment (MA) scenarios (Alcamo et al., 2006; Bennett and Carpenter, 2006; MA, 2005). The use of these scenarios for the year 2050 is as a baseline to analyse the additional inputs of N and P to rivers assuming large-scale land-based production of biodiesel from algae, by using the Global *NEWS* model. The analysis uses different scenarios, that either assumes replacement of fossil diesel for all traffic, or only for heavy traffic such as heavy duty trucks, freight vessels and airplanes in EU27 countries by biodiesel from algae. The focus on heavy traffic reflects the possibility that many private cars may be electric by the year 2050 and do not need fuels. This may be impossible for heavy traffic, making biodiesel an important alternative to fossil diesel (Mackay, 2010).

The Global *NEWS* model simulates the transport N, P and carbon (C) in multi-element form by more than 6000 rivers all over the world (Mayorga et al., 2010; Seitzinger et al., 2005). The first version of the model (Global *NEWS*-1) was released in the year 2005. This model system consisted of a set of sub-models which estimate dissolved inorganic nitrogen (DIN) and phosphorus (DIP), dissolved organic nitrogen (DON), phosphorus (DOP) and carbon (DOC), particulate nitrogen (PN), phosphorus (PP) and carbon (PC) (Billen et al., 2010; Bouwman et al., 2009; Fekete et al., 2010; Seitzinger et al., 2005; van der Hoek, 2001). In 2009 a revised Global *NEWS* model was released which combines all sub-models in one integrated interface. This Global *NEWS*-2 model estimates nutrient export from the watersheds to coastal waters at the mouth of rivers not only for the present, but also for the past and the future. The Global *NEWS* model uses global input data with a typical spatial resolution of 0.5 × 0.5 degree latitude by longitude. These input databases are generated by the IMAGE model and the Water Balance Plus model (Bouwman et al., 2009; Van Drecht et al., 2009; Fekete et al., 2010). Global *NEWS* has been validated at the global scale and not only been used for global analysis, but also for studies at the continental scale including Europe (Kroeze et al., 2002; Kroeze and Seitzinger, 1998; Qu and Kroeze, 2010, 2011; van der Struijk and Kroeze, 2010; Yasin et al., 2010) and the regional scale (Strokal and Kroeze, 2012; Thieu et al., 2010; Yan et al., 2010)

Global *NEWS* can be used to quantify the sources of nutrients in rivers. The nutrients in rivers originate from anthropogenic and natural sources. Natural sources are mainly diffuse sources, including N and P leaching and runoff from natural areas. The anthropogenic sources include diffuse and point sources. Agriculture, industry and human waste are important anthropogenic sources of nutrients in rivers. Sanitation is an important source of nutrients in many rivers (Van Drecht et al., 2009). In Global *NEWS*, nutrient inputs from sewage are calculated as a function of population density, sewage connection, and waste water treatment. Basin-specific removal efficiencies of waste water treatment plants are available in the model. The Global *NEWS* model calculates river export of nutrients while accounting for watershed and river retention. The model output includes the nutrients loads at the river mouths.

The Global *NEWS* model is used to calculate the additional river export of nutrients as a result of cultivation algae in river basins of the EU27 countries in the future. Algae parks on land are considered an additional point source of N and P to rivers in our study, following the modelling approach of point sources applied in Global *NEWS* (Van Drecht et al., 2009).

1.3. Millennium Ecosystem Assessment scenarios

The Millennium Ecosystem Assessment (MA) scenarios for 2050 function are as a baseline. The MA was initiated by the United Nations in 2000. The objective of the MA was to assess the consequences of ecosystem change for human well-being and provide a rigorous scientific basis for action needed to enhance the conservation and sustainable