Ecological Engineering 116 (2018) 154–162

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

# Early ecosystem responses to watershed restoration along a headwater stream

Emilie M.F. Kallenbach[a,b,*], Kaj Sand-Jensen[b], Jonas Morsing[c], Kenneth Thorø Martinsen[b], Theis Kragh[b], Karsten Raulund-Rasmussen[c], Lars Baastrup-Spohr[b]

[a] NIVA Denmark Water Research, Njalsgade 76, 2300 Copenhagen S, Denmark
[b] Freshwater Biological Section, Department of Biology, University of Copenhagen, Universitetsparken 4, 3. Floor, 2100 Copenhagen Ø, Denmark
[c] Section for Forest, Nature and Biomass, Department of Geosciences and Natural Resource Management, University of Copenhagen, Rolighedsvej 23, 1958 Frederiksberg C, Denmark

ARTICLE INFO

*Keywords:*
Ecological restoration
Oxygen conditions
Hypoxia
Forest clearance
Watershed restoration

ABSTRACT

Along many streams, natural riparian vegetation has been replaced by agricultural fields or plantations resulting in ecosystem alterations due to changes of the interactions across the land-water ecotone. We studied the effect of restoration interventions by removing a dense spruce plantation in a 25 m wide zone along a 4 km section of a headwater stream. Water discharge, nutrient and total organic carbon concentrations were unaffected by the intervention, which only involved 0.7% of the catchment area. Focusing on the oxygen dynamics within several sections of the stream revealed that the stream water was generally oxygen under-saturated both before and after the restoration reflecting the dominance of heterotrophy over photoautotrophy typical of small streams. Oxygen saturation was tightly coupled to water discharge, with anoxia or hypoxia developing during low summer flow, and levels just below saturation during high autumn-spring flow at low temperature and low metabolism. Stream-near felling increased incident irradiance and reduced the duration and extent of summer hypoxia despite unaltered discharge, temperature and concentration of total organic carbon. Increased incident irradiance was accompanied by higher oxygen saturation in open sections compared to control sections with intact tree cover. Diel oxygen changes followed incident irradiance during low summer flow, while alterations at high winter flow were caused by changes in temperature-dependent oxygen solubility and high reaeration. In conclusion, we show that anoxic or hypoxic oxygen levels occur in warm, low-flow summer periods and this stress is reduced when intense shading from spruce plantation is removed and in-stream oxygen production is stimulated.

## 1. Introduction

Streams play a major role in global elemental cycles and exhibit high biodiversity, even though they occupy < 0.6% of the Earth's land surface (Downing et al., 2012; Strayer and Dudgeon, 2010). Small streams account for the main length of the world's lotic waters and because of intimate connection to the terrestrial environment, their ecosystem processes and biodiversity are strongly affected by riparian land use (Downing et al., 2012; Friberg, 1997). Changes from natural riparian zones to plantations, agricultural fields and urban areas have deteriorated environmental conditions along countless streams (see references in González et al., 2017). Knowledge on the ecological effects of these historical alterations as well as recent restoration attempts are few, but important for proper management to re-establish good ecological status of streams.

We investigated the effect of restoration interventions, in which Norway spruce (*Picea abies* (L) Karst.) plantations were cleared to allow natural secondary succession in a 25-m wide zone along a 4 km section of a headwater stream on the island of Bornholm, Denmark. Clearing of the spruce vegetation close to the stream will reduce the atmospheric input of needles and branches that normally reaches the stream (Iversen et al., 1982), but in contrast could increase the hydrological input of dissolved organic carbon and nutrients (Huber et al., 2004; Oni et al., 2015). We assume this influence on carbon input and mineral elements to the stream are minor because the felled area comprised only 0.7% of the catchment area. We evaluated the influence by comparing stream transport before and after felling by calculating the potential change of input based on the size of the felled area. More importantly, felling the spruce trees along the stream may have an immediate and direct ecosystem effect by increasing light availability within the stream (Barbier et al., 2008). Alterations of the riparian zone vegetation may thereby influence stream water oxygen concentration by changing the balance

* Corresponding author at: Njalsgade 76, 2300 Copenhagen S, Denmark.
*E-mail address:* eka@niva-dk.dk (E.M.F. Kallenbach).

https://doi.org/10.1016/j.ecoleng.2018.03.005
Received 17 August 2017; Received in revised form 23 February 2018; Accepted 11 March 2018
0925-8574/ 

between primary production, respiration and atmospheric gas exchange (Odum, 1956). Increasing incident irradiance by removing the forest canopy should increase primary production in the stream and may result in higher daytime oxygen concentration. However, it could potentially also lower nocturnal oxygen concentration caused by higher biomass of respiring phototrophic organisms and higher water temperatures enhancing respiratory rates and reducing oxygen solubility (O'Driscoll et al., 2016). Change in water discharge, and consequently water level and current velocity, because of altered catchment vegetation may also have a direct influence on oxygen pools and atmospheric gas exchange (Brown et al., 2005; Raymond et al., 2012).

Even though oxygen levels serve as a primary indicator of ecosystem processes, and is a key-factor for habitat suitability, few investigations have directly evaluated the effect of stream-near clearing on oxygen conditions (Bernot et al., 2010; Bunn et al., 1999; Clapcott and Barmuta, 2010; DaSilva et al., 2013; O'Driscoll et al., 2016). Here, we present comprehensive analyses of oxygen conditions and associated environmental variables from one year before to two years after clearing of the stream-near spruce plantations along a headwater stream. The overall objective was to elucidate the effect of restoring the natural stream-near vegetation on the stream ecosystem using oxygen condition as our sentinel, and to gain knowledge on the effect of stream-near plantation removal as a restoration tool. We aimed at understanding the temporal variation of oxygen and the influence of seasonal changes of incoming irradiance and water discharge. Our specific hypotheses were that: 1) increasing light availability by removing the spruce plantation would increase primary production in the stream leading to higher daily oxygen concentrations in well illuminated periods and stream reaches, 2) because of the very low proportion of felled area in the catchment, changes in hydrology and concentration and transport of nutrients and carbon would be insignificant, and 3) because of the small size of the stream, the effect of the restoration was subordinate to seasonal changes caused by changes in temperature and precipitation.

## 2. Materials and methods

### 2.1. Study site

The study was conducted along the uppermost 4 km of the stream 'Øle Å', Bornholm, Denmark (Fig. 1). The stream originates from the protected wetland 'Ølene' and is unregulated, meandering through the rocky landscape with an average slope of 6.5 m $km^{-1}$ in the study reach. The nearby area including the riparian zone has been managed as a plantation since the beginning of the 19th century primarily with Norway spruce (*Picia abies* (L) Karst.), which was planted close to the stream on approximately 56% of the left stream bank and 54% of the right stream bank of the study reach. Few wet riparian stretches were left with natural mixed deciduous forests or herb communities.

#### 2.1.1. Restoration intervention

In autumn 2014, the dense spruce plantation was cleared in a 25 m wide belt along the stream (Fig. 1). In total, spruce plantation was removed on 6.5 ha, corresponding to 0.7% of the catchment area. The felling was made with minimum disturbance to the soil, particularly to the wet soils, the stream, and the existing natural vegetation. Tree stumps were left and a minimum of brash was allowed in the stream. After the intervention, the area was left to undergo secondary succession without any further intervention. In order to promote regrowth of deciduous trees, birch (*Betula* sp. L.), black alder (*Alnus glutinosa* Gaertn) and other native trees were left. In short sections along the stream one side of the stream bank was left un-cut, and at one 173 m long stretch both banks were left un-cut serving as a control (Fig. 1).

### 2.2. Monitoring stations

To ensure a proper coverage of the variability of environmental conditions and to evaluate the restoration effects, four monitoring stations were set up along the study reach (Fig. 1). Station 1 was located in mixed forest just upstream of the cleared areas. Station 2 was set in an area approximately halfway through the study reach, with intervened areas until about 50 m upstream. Station 3 was located in an entirely cleared area close to the end of the study reach. Station 4 was located at the end of the study reach in a mostly open area with a mixture of deciduous trees and spruce. Stations 1, 2, and 4 were monitored from 2013 to 2016, whereas Station 3 was added as a supplement for campaigns, 7 days in June 2015, from December 15, 2015 to January 12, 2016 and from the March 8 to May 12, 2016.

#### 2.2.1. Oxygen and temperature

Oxygen concentration and water temperature were measured at 10 min intervals at the stations using oxygen sensors (MiniDOT logger, Precision Measurement Engineering, Inc., Vista, Ca, USA). Before and after deployments, oxygen sensors were calibrated in 100% oxygen-saturated water bubbled with atmospheric air and 0% oxygen saturated water bubbled with nitrogen. Oxygen concentrations were corrected for drift (maximum 2%) during deployment assuming linear changes over time. Freezing during cold winter periods prevented proper sensor

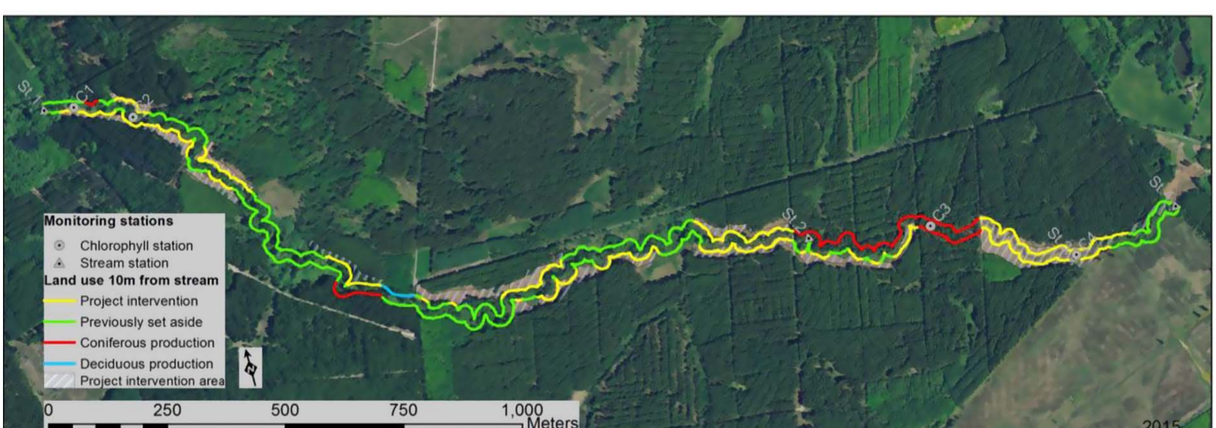


**Fig. 1.** Aerial photo from 2015 of the area along the upper Øle Å. The areas felled are indicated by zones with white stripes. To illustrate the different forest and vegetation type along the stream a line was drawn along the stream 10 m from each stream bank and coloured according to land use. Yellow are areas felled as a restoration intervention; green indicate previously set aside areas; red are control areas, where the spruce plantation is left intact; blue are areas with deciduous forest. Monitoring stations (St.) and chlorophyll sampling stations (C) are shown with grey triangles and dots, respectively. © COWI DDOl and 2015. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)