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Research Paper

Seasonal insect emergence from three different temperate lakes

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ABSTRACT

Knowing the aquatic resources, such as emerging insects, that are entering terrestrial systems is important for food web and conservation studies, especially when water availability or quality is limited. Even though studies concerning benthic macroinvertebrates are numerous, insect emergence from lakes is less studied.

To understand if water parameters (e.g., water temperature, oxygen concentration etc) determine insect emergence and the possible seasonal differences, we collected emergent insects from three different lakes in South Germany, during three seasons. We searched for common patterns of insect emergence at the three lakes. Moreover, the relative contribution of insects of aquatic origin to aerial flying arthropods was assessed, with collecting aerial flying arthropods at the shore.

Chironomidae constituted the highest number of emerged insects in all lakes, however different patterns of emergence occurred in each lake (unimodal vs. bimodal) with different season-dependent times for the emergence peaks (spring, summer, beginning of autumn). Aquatic insects constituted a considerable proportion (at least 17%) of the aerial flying arthropods at the shore. The variation in insect emergence was explained by water temperature, however not by other water parameters or the nutrient values. Seasonal and spatial differences in insect emergence, should be considered when investigating aquatic-terrestrial interactions and designing conservation plans. A total biomass of up to 1.8 g m^{-2} of emerging insects from the littoral zone of Lake Constance can enter the terrestrial system in a year. We also provide length-dry weight relationships for emerged (adult) Chironomidae. These equations are useful to estimate the dry insect biomass from length data and currently such data lack for adult aquatic insects.

1. Introduction

Material, energy, nutrient and organism fluxes can cross ecosystem boundaries and enter food webs of adjacent recipient systems in the form of subsidies. Subsidies are described as donor-controlled resources (prey, detritus, nutrients) from a given habitat to a recipient, where they can increase its productivity (Polis et al., 1997). Allochthonous (found in a place other than where they were produced) inputs can: increase food-chain length (Pimm and Kitching, 1987), influence food-web stability (Huxel and McCann, 1998; Takimoto et al., 2002), and energy, carbon, and nutrient flow in a recipient system (Polis et al., 1997).

The emergence of insects from freshwater systems is an example of potential subsidies that occur between aquatic and terrestrial systems. The life history of many aquatic insects includes larval stages in aquatic environments and an adult stage in terrestrial systems, therefore, movements across habitats occur. These emergent aquatic insects are important food sources for a great number of consumers, such as spiders, lizards, and several avian and mammalian species (see e.g., Akamatsu et al., 2004; Fukui et al., 2006; Lam et al., 2013; Sabo and Power, 2002a,b; Uesugi and Murakami, 2007). However, there is a gap of knowledge in the assemblage and emergence patterns of these insects, especially from lakes and in how these patterns relate to the lake's trophic condition. Variation in insect community composition can occur in a spatiotemporal scale, allowing aquatic insects as a useful tool in monitoring the ecological status of a lake by examining emerging insects (Raunio and Paasivirta, 2008). Moreover, studying the patterns of insect emergence provides important data on the availability of this essential prey resource to adjacent systems.

Water warming can have an impact on aquatic insect emergence phenology (Greig et al., 2012; Jonsson et al., 2015) and, indirectly, could also influence terrestrial food webs. The effects of water warming on insect emergence can be more complex in combination

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with other stressors, e.g. increase in nutrients and fine sediments (Piggott et al., 2015). Knowing and understanding the patterns of aquatic insect emergence in terms of seasonality, magnitude and species composition can help to predict how these might alter with climate change and to understand their effects on surrounding ecosystems. Additionally, aquatic bodies in many areas of the world are affected by human alterations that may influence negatively the freshwater ecosystem services, such as water quality or biodiversity (Dodds et al., 2013). Knowledge on aquatic-terrestrial trophic interactions could help set priorities in conservation policies focusing on animals and water bodies.

To understand insect emergence, it is essential to know which factors influence it and how. Aquatic insect emergence is naturally related to zoobenthic communities. However, same factors can influence each in different ways or extent. For instance, fish predation was found to have a stronger effect on emerging insects than on their benthic larval stages (Wesner, 2016). Although there are many studies concerning the factors that influence benthic macroinvertebrates, such as habitat structure, trophic status, wind-induced disturbance (Cai et al., 2012) and oxygen concentration (Craig et al., 2015), more studies are needed to clarify the influence of those factors to the insect emergence.

Traditionally, research focuses on subsidies from terrestrial to aquatic systems, rather than the opposite direction (e.g., Finlay and Vredenburg, 2007; Polis et al., 1997). Also, trophic relations between lentic ecosystems and terrestrial consumers have been less studied (but see Mehner et al., 2005; Kraus, 2010; Scharnweber et al., 2014) than lotic systems (e.g., Kawaguchi and Nakano, 2001; Sabo and Power, 2002a,b). Bartels et al. (2012), that did a *meta*-analysis on subsidy inputs across freshwater-terrestrial ecosystems, found that only 7.2% of all observations were referring to lentic ecosystems as opposed to lotic. Thus, our aims were: i) to assess the aquatic biomass (from lakes) that is transferred into the adjacent terrestrial system, ii) to determine general patterns in insect emergence at three different lakes, in the same region, with respect to season, and iii) to investigate the effect of water parameters, such as temperature, oxygen concentration, pH, and nutrients, on insect emergence. We collected emerged aquatic insects during spring, summer and autumn at three lakes (of different size and trophic condition), in South Germany. Furthermore, we addressed questions on the availability of these aquatic insects to terrestrial systems by looking into aerial flying arthropods, in spring and summer. To estimate and compare the biomass of aquatic insects from the three lakes to their adjacent terrestrial systems, we calculated length-weight relationships for the most common aquatic insect taxa. There are several studies with estimates of length-weight relationships of benthic macroinvertebrates from lakes (e.g. Benke et al., 1999; Baumgärtner and Rothhaupt, 2003; Mährlein et al., 2016), nevertheless there is a lack for these estimations for adult aquatic insects.

2. Materials and methods

2.1. Study sites

The study was conducted at three lakes in South Germany (Fig. 1) that differ in size and trophic status. Lake Constance is a deep (max. depth 254 m), large (500 km^2), pre-alpine, oligotrophic lake, situ-

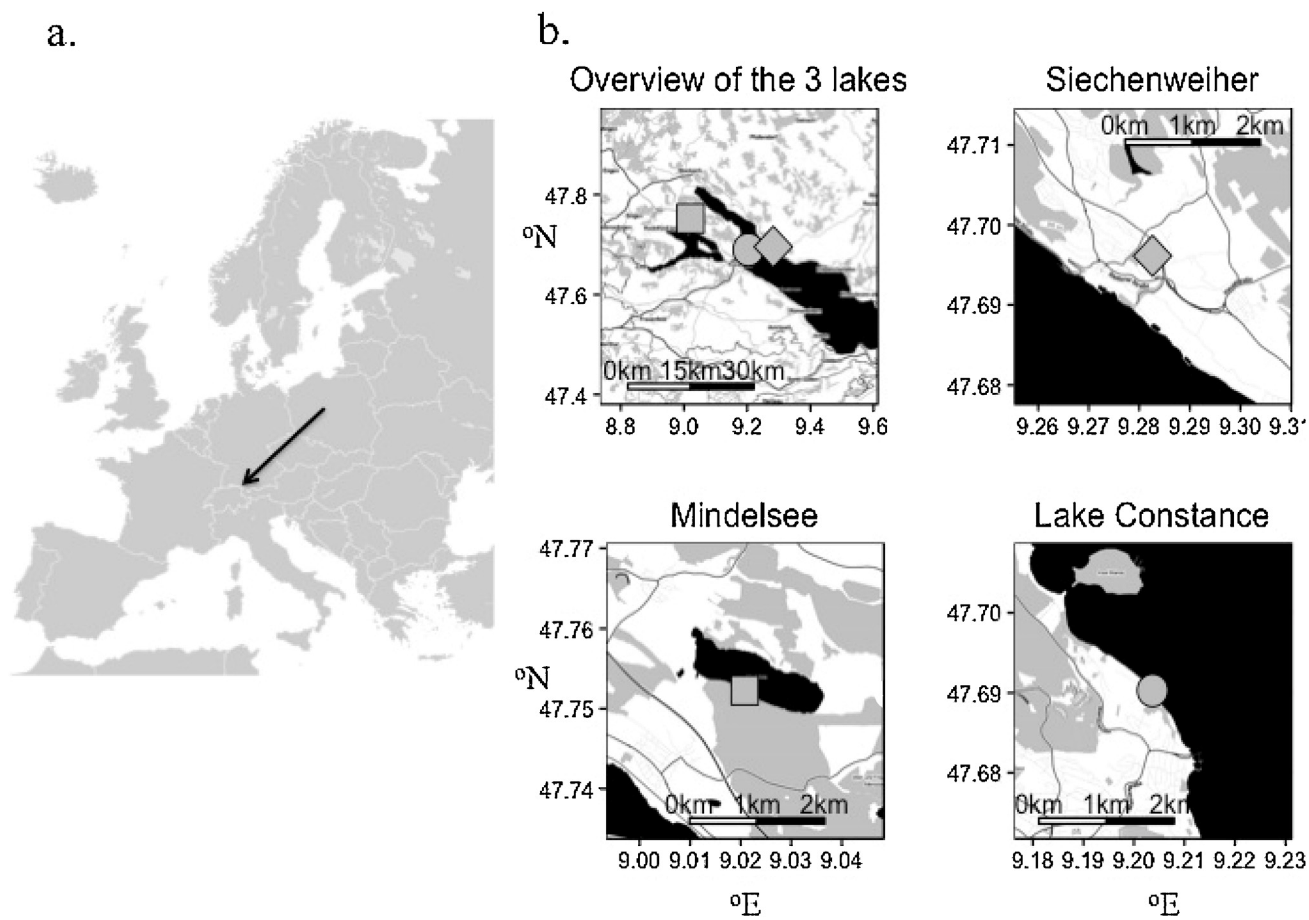

Fig. 1. a. Study area. Map of Europe (commons.wikimedia.org) where the study area is indicated with an arrow and, b. of the region with the lakes (upper left) and the sampling location in each lake (google maps): Lake Constance, Mindelsee, Siechenweiher. Maps with latitude and longitude (N: North, E: East).