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### The landscape drives the stream

*Unraveling ecological mechanisms to improve restoration*

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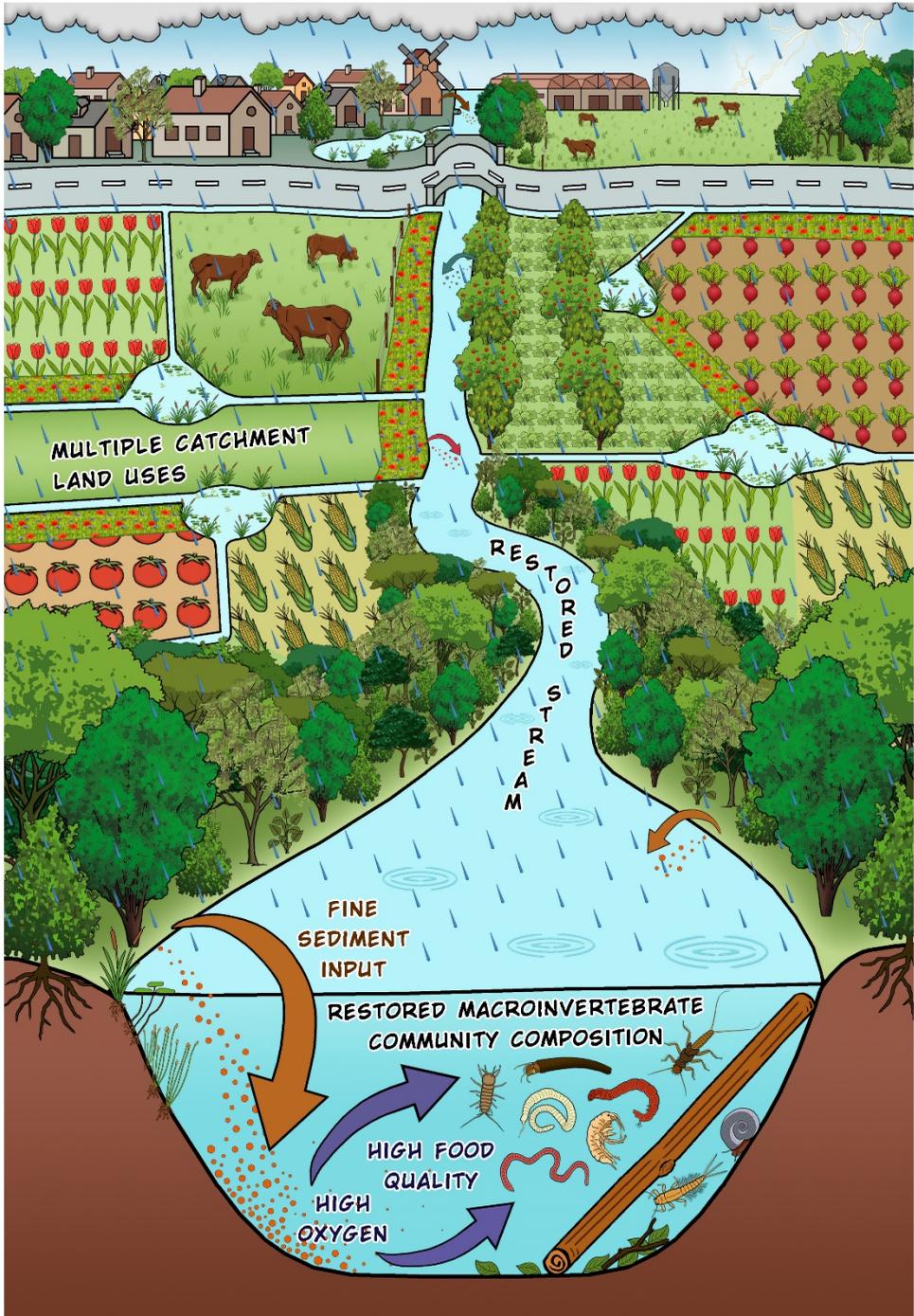
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# Chapter 7

Synthesis

The influence of surrounding land use on stream ecosystems is scale-dependent (Frissell et al., 1986), whereby instream habitat structure and organic matter inputs are determined primarily by local conditions such as vegetation cover, whereas nutrient supply, sediment input, hydrology and channel characteristics are influenced by regional conditions, including landscape features and land use types at some distance upstream and lateral to each specific site (e.g., Allan et al., 1997). Yet, the underlying mechanisms linking adverse in stream ecological effects to stream valley land use are still not fully understood. The aim of this thesis was therefore to unravel the mechanisms by which land use affects structure and functioning of lowland stream ecosystems. There are several potential mechanisms by which land use type can affect stream ecosystems (e.g. Burcher et al., 2007; Maloney and Weller, 2011), including the input of land use specific terrestrial particles into the stream, the focus of the present thesis.

In the present thesis we showed that allochthonous particulate matter, either organic or mineral (silt) entered the lowland streams and deposited in stream deposition zones. This material changed the natural substrate cover and sediment characteristics (chapter 3, Wood and Armitage, 1999). These changes altered both stream ecosystem structure (e.g., macroinvertebrate community composition) and functioning (e.g., oxygen regime and metabolism) (chapter 4, Buendia et al., 2013). The macroinvertebrate community composition in turn responded to the changed environmental conditions in the deposition zones (chapters 3, 4, 5 and 6). These findings are in line with, amongst others Chutter (1969), Ryan (1991), Rabeni et al. (2005) and Von Bertrab et al. (2013). The present thesis thus contributed to a better understanding of the effects of land use on stream metabolism and oxygen availability (chapters 3 and 4) and habitat structure and food resources (chapters 3 and 5). Moreover, the ecological key factors oxygen, habitat structure and food resources were shown to interact (chapter 5) shaping lowland stream ecosystems (e.g. Hunt et al, 2012; Wallace et al., 2015). In chapter 6 an experimental attempt to restore these interrelated ecological key factors was presented.

To both better understand land use specific stressor-response pathways and to support restoration practices, below we elaborated a framework integrating the results obtained from the previous chapters. To this purpose the elements of the framework that describe the effects of land use on lowland stream macroinvertebrate communities were described as land use pressure, stress, disturbance of ecological key parameters and abiotic and biotic responses, analogous to the DPSIR framework

(driver, pressure, state, impact and response) (see van Puijenbroek, 2019). Subsequently, the framework was applied per land use type, aiming to design a land use specific effect framework.

## 1. The effects of land use on lowland stream macroinvertebrate communities

### 1.1 Land use induced stress

Human activities in the landscape, such as the use of fertilizers, ploughing, the presence of livestock (e.g. Jarvie et al., 2010), forestry (Moore et al., 2006) and the treatment of wastewaters (Walsh et al., 2005) change the nature and composition of dissolved substances and fine particulate material input into the streams. These dissolved substances (mainly nutrients and pollutants) and organic and mineral particles, further indicated as sediment, are easily washed off from the terrestrial surrounding into stream ecosystems by diffuse runoff (Chapter 3, Cai et al., 2015; Vidon et al., 2010). Wastewater treatment plants (WWTP) are point sources of nutrients and fine organic particles (e.g. Carey and Migliaccio, 2009). Input of nutrients and sediment from the adjacent land is a dominant fuel for lowland streams that depend on energy input from the surrounding valley and catchment (Hoellein et al., 2013; Bernhardt et al., 2018). Consequently, anthropogenic land use will affect lowland stream ecosystem structure and function, as it changes the fuel provided to the system (e.g., Allan, 2004; Castro et al., 2018; Englert et al., 2015; Frainer and McKie, 2015; Hladyz et al., 2011; Masese et al., 2017; Riipinen et al., 2010).

Lowland stream valleys covered by forest provide large amounts of allochthonous material, such as woody debris, tree leaves and coarse, fine and dissolved organic matter to the stream (Bilby, 1981; Meyer et al., 1998). However, when the land use in the valley is changed, the load of dissolved substances, substrate cover and sediment composition may also change dramatically. For example, runoff from agricultural areas may contain microbial pathogenic organisms, nutrients, potentially toxic substances (e.g., pesticides), metabolic substrates (e.g., labile organic carbon) and fine mineral and organic grains (Khaleel et al., 1980; Jordan et al., 1997; Edwards et al., 2008). Grassland in comparison to cropland will, to a certain extent, limit sediment runoff and will retain more sediment and sediment-bound pollutants (Souchère et al., 2003; Burcher and Benfield, 2006; Withers and Jarvie, 2008). WWTPs discharge high loads of dissolved nutrients into streams (Gücker et al., 2006; Imberger et al., 2014).

In conclusion, land use can have strong effects on lowland stream structure and functioning and is considered to be therefore a major stressor (Pozo et al., 1997;

Lambert et al., 2017). To improve our understanding of the underlying mechanisms as aimed in the present thesis, the land use - stream ecosystem interaction was put in a conceptual framework (Figure 1). Four major land use types, each providing different inputs into the receiving streams were distinguished: 1- Forest with CPOM (woody debris and coarse organic matter, like branches, twigs and leaves) runoff; 2- Grassland with nutrient-rich organic particles runoff; 3- Cropland with fine sediment runoff; 4- WWTP with point discharge of dissolved nutrients (Figure 1). The input types 2-4 were considered to be a major stressor for lowland stream ecosystems.

### *1.2 Disturbance of ecological key factors*

The discharge of dissolved substances and sediment into the streams influences the morphological and physico-chemical instream characteristics, and changes for example oxygen and nutrient concentrations, grain size and metabolic rates (e.g. Young et al., 2008), therewith disturbing the ecological key factors. Figure 1 illustrates the ecological key parameters that can be changed by land use stress.

Dissolved nutrients and organic sediment change primary production and ecosystem respiration, respectively, together defining the whole stream metabolism. These changes result, amongst others, in changes in oxygen concentration and diel oxygen regimes. Moreover, increases in sediment input can lead to a lower transparency (poorer light conditions) in the water column. Less light causes less growth of algae and macrophytes and lower primary production and related oxygen availability. Higher organic sediment input causes higher turbidity and increased decomposition rates. Such a cascade of events underlines the importance of autotrophic and heterotrophic metabolic processes, as previously suggested by Johnson et al. (2009), Battin et al. (2016), Lear et al. (2013), Price et al. (2018), Hunt et al. (2012), Kendall et al. (2001) and Leigh et al. (2010).

Input of coarse organic matter (e.g. woody debris) from forested riparian zones or growth of macrophytes due to nutrient input will both change the instream flow patterns (e.g. Jones et al., 2012a) and habitat structures (e.g. Schoelynck et al. 2012).

### *1.3 Abiotic responses and subsequent changes in macroinvertebrate community composition*

The macroinvertebrate community composition is influenced by the type of organic matter in the sediment as major food source, being either allochthonous (e.g., wood, CPOM, FPOM) or autochthonous and when autochthonous being either autotrophic (e.g. macrophytes and algae) or heterotrophic (e.g. bacteria and fungi)

(e.g., Cummins and Klug 1979; Wallace and Webster 1996; Johnson et al., 2009). So, macroinvertebrate community composition is expected to change when changes in food quality occur (Cammen, 1980; Cummins and Klug, 1979). Species belonging to the Ephemeroptera, Plecoptera and Trichoptera (EPT-species) may take advantage of the presence of allochthonous material, like CPOM and FPOM which have high C/N ratios (Besemer et al., 2009; Boyero et al., 2011; Von Bertrab et al., 2013). Furthermore, changes in the stream structure by woody debris, leaf packages, FPOM depositions and macrophytes will alter the habitat structure and therewith the composition of the macroinvertebrate communities (Brown, 2003; de Brouwer et al., 2019).

Oxygen is a key ecological driver for macroinvertebrates (Boulton et al., 1997; Fox and Taylor, 1955). Low oxygen concentrations in either the water column or the sediment limit the occurrence of many EPT-species (Connolly et al., 2004; Collier et al., 1998; Von Bertrab et al., 2013). Other species that tolerate low dissolved oxygen concentrations, such as *Chironomus* sp., Oligochaeta and some Gastropoda can dominate under disturbed oxygen conditions (Ding et al., 2016; Justus et al., 2014; Pardo and García, 2016).

It is concluded that stress-induced land use specific changes in ecological key parameters may induce abiotic responses of the system, concerning food quality, oxygen availability and habitat structure (Figure 1). This undoubtedly has consequences for the macroinvertebrate community composition.

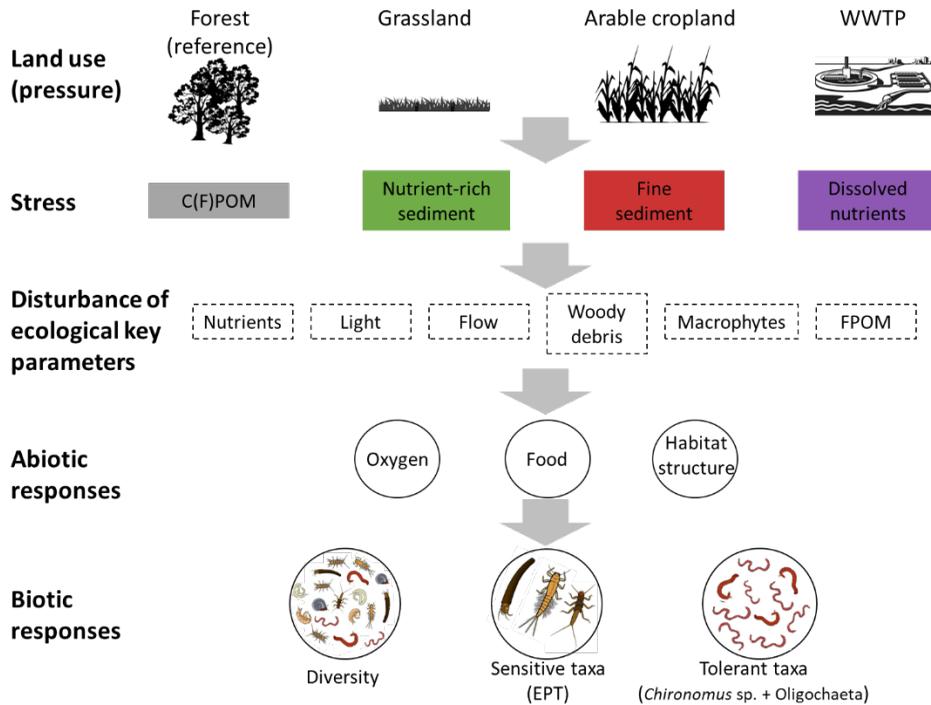


Figure 1: General pressure (land use) - response (macroinvertebrates) framework. Rectangles in color represent the terrestrial input, dashed rectangles show the ecological key parameters that may be disturbed and circles symbolize abiotic responses in terms of oxygen, food and habitat structure and biotic responses in terms of macroinvertebrate community composition.

## 2. Towards a land use specific effect framework

### 2.1 Introduction

Each land use type has specific multiple impacts on stream ecosystems. To facilitate the study of the complex relationships between stressors (land use type) and biotic responses (macroinvertebrate community composition), the major pathways have to be identified (e.g. Grace et al., 2010; Allan et al., 2012; Villeneuve et al., 2018). To do so, I designed the conceptual framework depicted in Figure 1. This framework is composed of four main layers including (1) land use stressors, (2) disturbances of ecological key parameters, (3) abiotic response and (4) biotic responses, respectively (Figure 1). Below, the building blocks of the framework were connected by positive and negative pathways running from land use type (stressor) to lowland stream ecosystem response (macroinvertebrate community composition).

2.2 Forest - C(F)POM input (reference condition)

In forests and forested riparian zones, the allochthonous input of coarse and fine particulate organic material (C(F)POM) controls lowland stream ecosystem structure and functioning (e.g. Lange et al., 2011). In the stream channel, CPOM creates heterogeneous substrate mosaics and diversifies flow patterns, creating conditions favorable for rheophilic and EPT species (chapter 6). Moreover, CPOM and FPOM largely determine the sediment characteristics in terms of food resources, being composed of microbial derived fatty acids and characterized by a high C/N ratio (chapter 5). Furthermore, shading that lowers metabolism and flow that increases re-oxygenation jointly result in relatively high and constant dissolved oxygen concentrations and low sediment oxygen demands. These conditions offer opportunities for xenosaprobic and oxyphilic macroinvertebrates species (Figure 2).

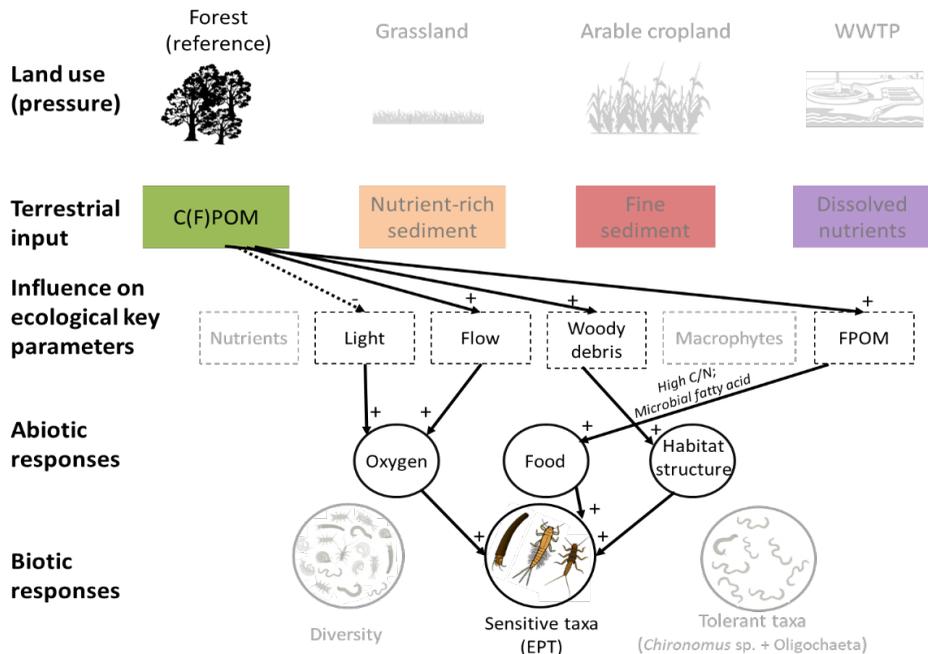


Figure 2: Forest (reference) pressure-response framework. Rectangles in color represent the terrestrial input, dashed rectangles show the influence on ecological key parameters and circles symbolize abiotic responses in terms of oxygen, food and habitat structure and biotic responses in terms of macroinvertebrate community composition. Pathways are illustrated by positive (+ solid line) and negative (- dashed line) connecting arrows.

2.3 Grassland - nutrient-rich sediment input

Streams surrounded by grasslands receive light, nutrients and organic sediment (chapter 3 and 4). The nutrients enhance the growth of macrophytes (Haggard et al., 2005) and algae, the latter increasing the chlorophyll concentrations in the sediment. Macrophytes structure the stream channel (Jones et al., 2012a), and together with the algae increase primary production rates (Finlay, 2011; Bernot et al., 2010; Mulholland et al., 2008). Plant production increases plant biomass and the decaying plants do increase respiration rates. Productivity and respiration together affect the diel oxygen regime. Most of the time, oxygen concentrations do not fall below 2 mg/l and are not limiting the occurrence of most macroinvertebrates. Only some sensitive species, like the oxybionts and the xenosaprobic ones, may disappear (Figure 3).

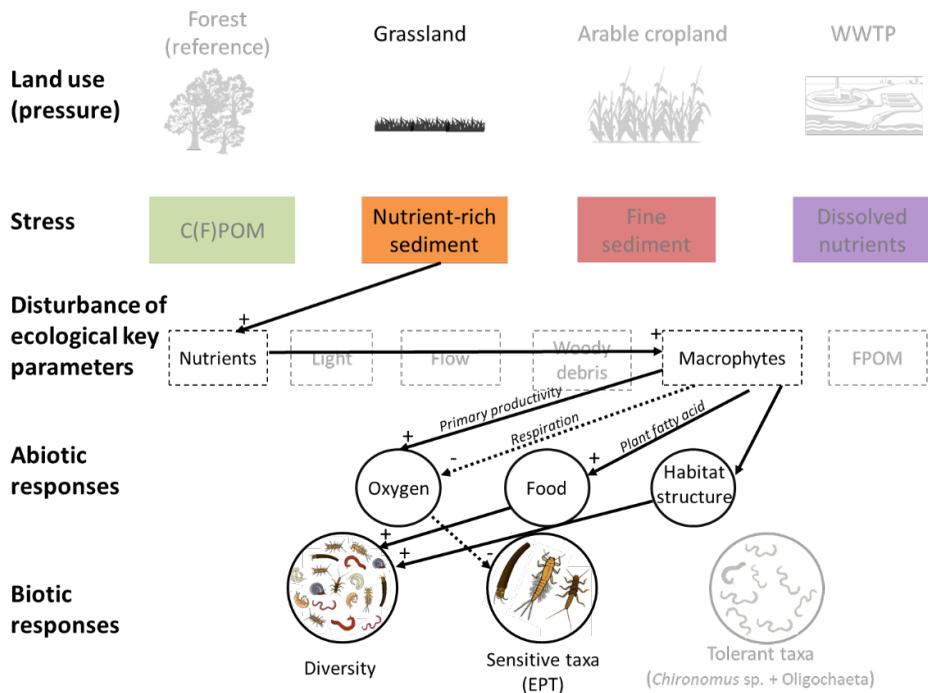


Figure 3: Grassland pressure-response framework. Rectangles in color represent the terrestrial input, dashed rectangles show the disturbed ecological key parameters and circles symbolize abiotic responses in terms of oxygen, food and habitat structure and biotic responses in terms of macroinvertebrate community composition. Pathways are illustrated by positive (+ solid line) and negative (- dashed line) connecting arrows.

2.4 Arable cropland - fine sediment input

Cropland runoff containing high loads of nutrient rich organic and mineral sediment (silt) do increase water turbidity and silt cover, especially in deposition zones. High water turbidity hampers the development of autotrophic organisms (Jones et al., 2012a; Vermaat and de Bruyne, 1993), despite the high nutrient concentrations, while at the same time heterotrophic microorganisms flourish (Stewart and Franklin, 2008). These processes affect the whole stream metabolism and decrease oxygen concentrations. The low oxygen availability limits the occurrence of oxyphilic species (Connolly et al., 2004), while tolerant taxa such as *Chironomus* sp., Oligochaeta and Gastropoda (Ding et al., 2016; Justus et al., 2014; Pardo and García, 2016) take advantage of heterotrophic microbial derived food (de Haas et al., 2005; chapter 4) (Figure 4). Moreover, fine sediment (silt) covers most of the stream bottom and limits the habitat availability for many macroinvertebrates and may even cause physical effects on macroinvertebrates such as disruption of organ function by clogging (Jones et al., 2012b).

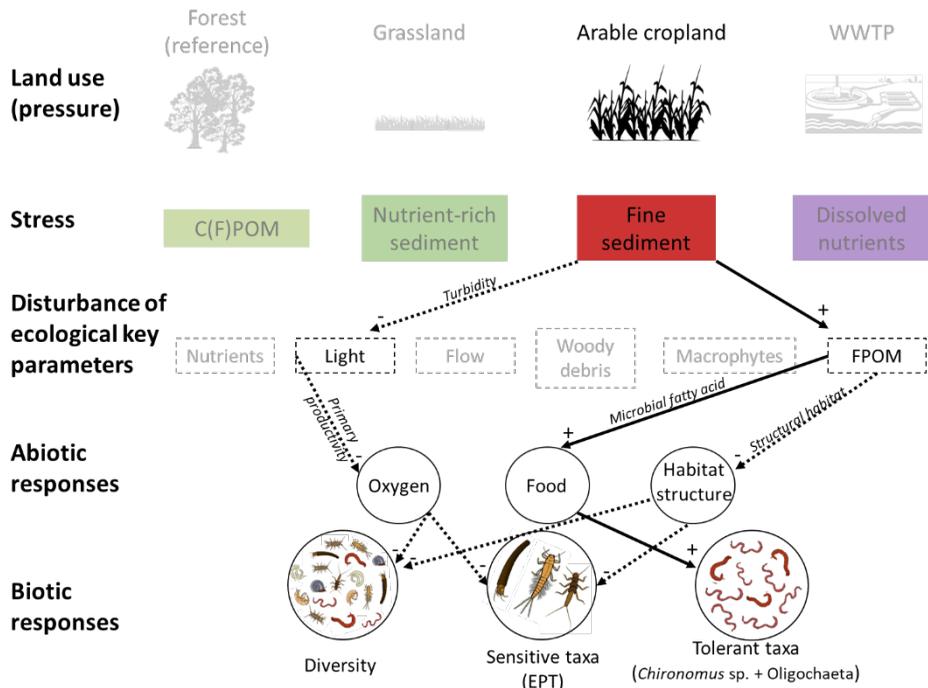


Figure 4: Cropland pressure-response framework. Rectangles in color represent the terrestrial input, dashed rectangles show the disturbed ecological key parameters and circles symbolize abiotic responses in terms of oxygen, food and habitat structure and biotic responses in terms

of macroinvertebrate community composition. Pathways are illustrated by positive (+ solid line) and negative (- dashed line) connecting arrows.

2.5 Wastewater treatment plant - dissolved nutrients input

Wastewater treatment plants discharge high nutrient loads into the receiving stream (e.g., Peterson et al., 1993; Wood and Armitage, 1997; Walsh et al., 2005). Moreover, WWTPs can cause typical hydrologic flashiness (Meyer et al., 2005; Walsh et al., 2005). The continuous input of nitrate, orthophosphate and oxygen into the water column stimulates the microbial community growing on the top sediment layer (Bernhardt and Likens, 2002; Bernot et al., 2006; Stewart and Franklin, 2008; Battin et al., 2016) and increase the benthic metabolic activity. Consequently, the oxygen availability in the sediment is expected to be low, which in turn affects the macroinvertebrate community composition (chapter 4). Sensitive taxa are limited due to the low oxygen availability, and tolerant taxa (often Oligochaeta and *Chironomus* sp.) are abundantly present (Figure 5).

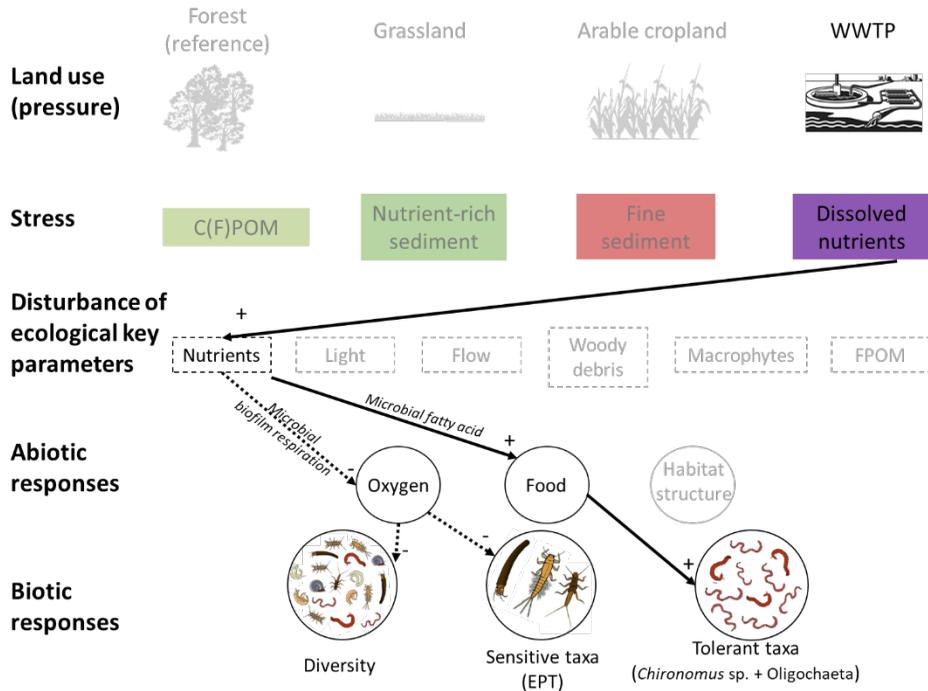


Figure 5: WWTP pressure-response framework. Rectangles in color represent the terrestrial input, dashed rectangles show the disturbed ecological key parameters and circles symbolize abiotic responses in terms of oxygen, food and habitat structure and biotic responses in terms of macroinvertebrate community composition. Pathways are illustrated by positive (+ solid line) and negative (- dashed line) connecting arrows.

2.6 Patchy landscapes

In patchy landscapes with multiple land use types, common to the mosaic like landscapes of deltas harboring lowland streams, the relationships between pressures-stressors-disturbances-responses are expected to be even more complex (Figure 6). In such cases it is crucial to identify the main pressures and related stressors per stream stretch and in turn relate these to the disturbances of the ecological key parameters and the abiotic responses affecting macroinvertebrate community composition (e.g. de Vries et al., 2019). This way, environmental problems can better be identified and tackled, resulting in a more effective set of measures to combat aquatic ecosystem degradation and to restore biodiversity.

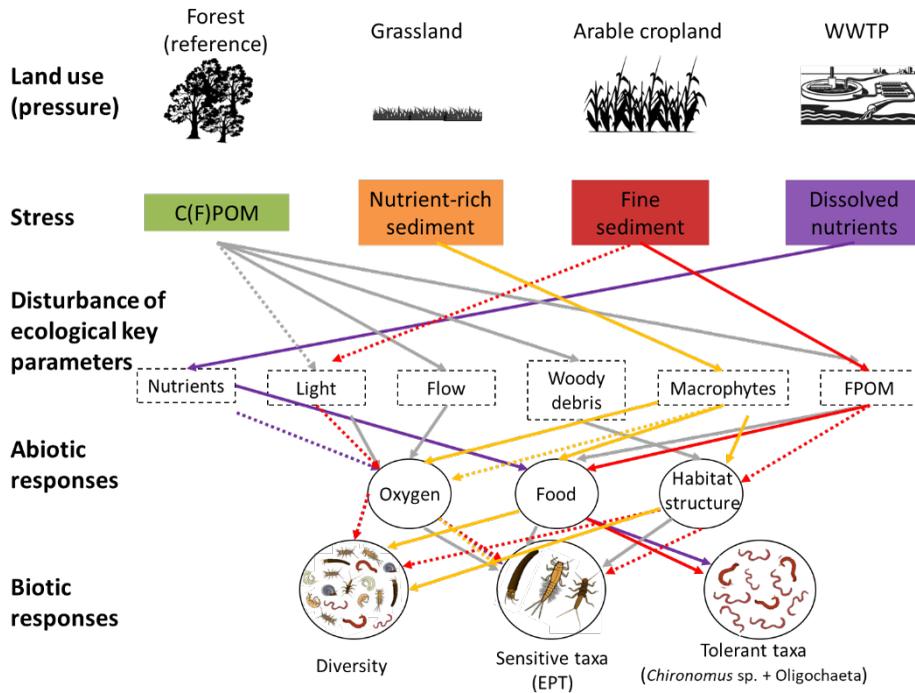


Figure 6: Pressure-response framework for patchy landscapes. Rectangles in color represent the terrestrial input, dashed rectangles show the disturbed ecological key parameters and circles symbolize abiotic responses in terms of oxygen, food and habitat structure and biotic responses in terms of macroinvertebrate community composition. Pathways are illustrated by positive (+ solid line) and negative (- dashed line) connecting arrows.

### 3. Conclusions

Based on the results obtained in the present thesis, the following conclusions can be drawn:

- Land use specific impacts on lowland streams are exerted via the accumulation of particles in deposition zones.
- Oxygen availability, habitat heterogeneity and food resources are considered key ecological filters driving macroinvertebrate community composition.
- We demonstrated the importance of including the landscape scale and multiple interconnected parameters in ecological stream quality assessments, yet the proposed framework needs to be tested in practice.

Hence, in this thesis I showed that the landscape indeed drives the stream and that only by unravelling the underlying mechanisms restoration measures may be improved.

### 4. Implications for stream restoration

The present thesis underlines the importance of including landscape scale anthropogenic activities in ecological stream assessments and restoration. This knowledge should be considered in designing stream restoration projects as follows:

1. Identify the input of particles and nutrients from different anthropogenic sources. As land use specific inputs of particles and nutrients influence stream ecosystem structure and function by changing dissolved substances concentrations and sediment composition, the need to identify the characteristics, such as volume and composition, is crucial in selecting the appropriate restoration measure. Such an approach may help to identify the main stressors, the pathways of disturbances and the macroinvertebrate community responses.
2. Design land use specific stream restoration strategies. The results obtained in the present thesis show that each anthropogenic activity has a specific impact on stream ecosystems. Therefore, to improve stream restoration success, restoration measures should take these pathways of stress and disturbance into account. Using the knowledge of land use specific effects on macroinvertebrate community composition allows to design tailor made restoration strategies.
3. Improve WWTP effluent quality and manage discharge. WWTPs change stream hydrology and water quality. Effluent nutrient loads must be lowered, and

effluent hydrological flashiness should be eliminated to ecologically restore streams affected by WWPT effluent discharge.

4. Retain water, sediments and nutrients at the source. The runoff of dissolved substances and sediment should be minimized and retained either on or close to the source. Buffer zones that store water and retain nutrients strongly add to stream restoration.
5. Develop and stimulate natural and sustainable land use types along streams. Keeping a natural vegetation corridor along a stream will filter particles and nutrients and subsidize the stream ecosystem with more natural materials. However, the application of this measure can cause economic conflicts. Developing agroforest along a streambank instead of tradition agricultural activities maintains a buffer function, while simultaneously supporting agriculture.

Streams are beautiful and complex ecosystems. They are not stand alone systems, but are part and product of relationships that include the atmosphere, hydrosphere, biosphere, lithosphere, and anthroposphere. In science, we are in a continuous process of growing understanding of these relationships, which hopefully contributes to bridge the science of stream ecology and ecological stream restoration practice. However, the impoverishment of the worlds streams and the losses of species and ecosystem processes proceeds faster than the growth in knowledge. As long as the rights of a stream, such as to freely flow and to be free of (excess of) nutrients and contaminants, are not respected and legally incorporated in our societies, I believe that there will be no way to fully enjoy, understand and reveal the mechanism by which the landscape drives the stream.