

Four Decades of Progress in Monitoring and Modeling of Processes in the Soil-Plant-
Atmosphere System: Applications and Challenges

Feedbacks between vegetation, surface structures and
hydrology during initial development of the artificial
catchment 'Chicken Creek'

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Abstract

Our investigations at the artificial catchment 'Chicken Creek' in Lusatia/Germany aim to disentangle and understand the feedback mechanisms and interrelationships of processes and their co-development with spatial and temporal structures and patterns by studying this initial, probably less complex ecosystem. Intensive measurements were carried out in the catchment with regard to the development of surface structures, hydrological patterns, and vegetation dynamics.

During the first seven years, considerable changes within the catchment were observed. Both internal and external factors could be identified as driving forces for the formation of structures and patterns in the artificial catchment. Initial structures formed by the construction process and initial substrate characteristics were decisive for the distribution and flow of water. External factors like episodic events triggered erosion and dissection during this initial phase, promoted by the low vegetation cover and the unconsolidated sandy substrate.

The transformation of the initial geo-system into areas with evolving terrestrial or aquatic characteristics and from a very episodic to a more permanent stream network and discharge, together with the observed vegetation dynamics increased site diversity and heterogeneity with respect to water and nutrient availability and transformation processes compared to the more homogenous conditions at point zero.

The processes and feedback mechanisms in the initial development of a new landscape may deviate in rates, intensity and dominance from those known from mature ecosystems. It is therefore crucial to understand these early phases of ecosystem development and to disentangle the increasingly complex interactions between the evolving terrestrial and

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aquatic, biotic and abiotic compartments of the system. Artificially created catchments could be a suitable tool to study these initial developments at the landscape scale under known, designed and defined boundary conditions.

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Keywords: ecosystem development; soil formation; vegetation succession; pattern formation

1. Introduction

The study of initial, artificially created ecosystems at a landscape scale could be an appropriate alternative to overcome many of the disadvantages encountered in natural catchments since boundary conditions and internal structures as well as initial site conditions can be better defined [1]. Whereas individual components of ecosystems have been studied in detail during ecosystem development, less attention has been directed to the complex interaction of biotic and abiotic ecosystem components during co-development and interacting effects of spatial patterns and processes on the development of ecosystem functions and stages [2-4]. Current research indicates the importance of hot spots and patches as starting points of initial development [5].

In this paper we present results about the development of patterns and structures during the first seven years of an artificial catchment starting from point zero. The 'Chicken Creek' project is a joint initiative of the BTU Cottbus, TU München and ETH Zurich. Our approach aims to disentangle and understand the feedback mechanisms and interrelationships of processes and their co-development with spatial and temporal structures and patterns by studying an initial, probably less complex ecosystem [6]. Structures and patterns in this context are biotic and abiotic properties of an ecosystem with explicit spatial, physical and/or chemical distributions that influence the extent, direction and duration of processes of ecosystem development. Structures are interacting with processes and initial structures are influencing the system development as well as the evolution of resulting new structures. Colonizing species during succession are defined as biotic structures. The spatial composition of biotic structures results in patches. The Chicken Creek project elucidates feedbacks between the different evolving structures, particularly between abiotic and biotic components of ecosystems.

2. Materials and methods

The artificial catchment 'Chicken Creek' was constructed in the post-mining area of the Lusatian lignite-mining district in eastern Germany. The region is characterized by temperate seasonal climate (559 mm mean annual precipitation, 9.3° C mean annual air temperature). The site is located in the middle of the still active open-pit mine 'Welzow-Süd', 20 km south of Cottbus. The catchment consists of a clay layer (174,000 m³, 1 - 3 m thickness) at the bottom as an aquiclude covered by a layer of Pleistocene sediments (117,500 m³, up to 3.5 m thickness) composed of sandy to loamy sandy substrate as aquifer. Details of the construction process and initial site conditions are given by previous publications [1, 7]. The catchment size is 6 ha with a SE exposition and a mean slope of 3.5 % (Fig. 1a). The site was prepared to allow for the formation of a small pond (0.4 ha) in the lower part of the catchment. No additional restoration measures like fertilization, planting or seeding were carried out and the site was left to natural development.

Immediately after construction was completed in September 2005, initial monitoring installations were set up oriented along a 20 x 20 m grid that covers the whole catchment (Fig. 1b). This setup was continuously complemented with additional measurements and installations to cover developing surface

structures and patterns. More details on the monitoring program and analytical methods are described in [8] and [9].

Since the Pleistocene sediments were dumped in two main phases, substrate characteristics differ slightly within the catchment. Whereas the eastern part is composed of almost pure sands (> 80 % sand), in the western part loamy sands dominate (70 – 80 % sand). Gravel content in both parts is 8 – 15 %. All substrates are slightly calcareous (< 0.1 mg N_T g⁻¹; 0.6 – 1.1 % CaCO₃) with high pH (7.7 – 8.1). Total nitrogen and organic carbon contents are very low (1.6 – 2.2 mg C_{org.} g⁻¹). Grid sampling at 124 grid points showed no differentiation of these parameters with soil depth.

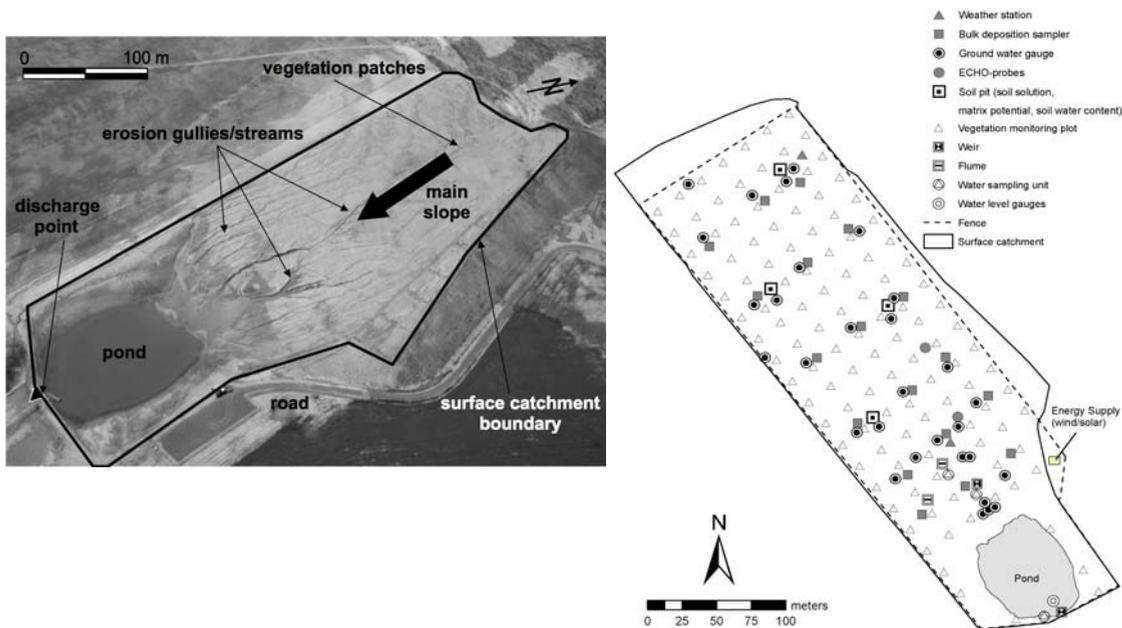


Fig. 1. (a) Aerial view and main features of the artificial catchment 'Chicken Creek' near Cottbus, NE Germany in May 2007, 18 months after finishing of the construction works (top); (b) Overview over grid points and monitoring installations at 'Chicken Creek' (right)

A microdrone (MD4-200 by microdrones GmbH, Germany) equipped with an optimized commercial digital camera (Pentax Optio A40 with 4000 x 3000 pixels) was used for the documentation of surface structures in the catchment. The system allows GPS waypoint navigation and programming of flight routes. The drone based aerial photos were geo-referenced using 178 ground-control-points (GCPs) including the 20 x 20 m grid points and additional GCPs in the pond and along the surface boundary of the catchment using WGEO software. The complete aerial photo of the whole catchment was composed of a mosaic of approximately 130 geo-referenced image blocks. The aerial maps were created using ArcGIS.

Vegetation succession was analysed using the 20 x 20 m grid (Fig. 1b) to implement a systematic net of permanent plots of 5 x 5 m with the grid mark in the plot centre. On each plot, all vascular plant species were recorded and the cover per species was estimated annually (for details see [10]).

Three weather stations were installed in the catchment (Fig. 1b). Station 1 is located in the upper part of the catchment recording wind speed and direction, air temperature and humidity, and global radiation in 2 m height and precipitation in 1 m height in hourly intervals since September 2005. A second station

was added in February 2008 in the lower part of the catchment with three recording levels (0.5, 2 and 10 m) and higher temporal resolution. The third station was installed in 2012 because fast growing trees in the direct vicinity influencing the measurements increasingly affected station 1.

Within the catchment, 30 observation wells were installed to record groundwater levels (Fig. 1b). 17 of them were installed along the grid points immediately after the completion of the Chicken Creek catchment. The boreholes were drilled manually down to the clay layer. The gauges were constructed using 2" PE-pipes. The lower part of the pipes (1 m) is perforated with 0.3 mm slots and the lower ends closed with caps were placed some centimeters into the clay. Nine gauges were equipped with water level loggers (pressure transducers). The groundwater level in the remaining wells was measured manually at least monthly.

Total discharge was measured in the clay dam at the bottom end of the catchment as discharge from the pond (Fig. 1b) using a V-notch weir combined with a tipping bucket to account for a large variation in discharge amounts. In September 2006, this weir had to be reconstructed resulting in a lowering of the discharge level by 37 cm (cf. Fig. 5). In addition, water levels in the pond were recorded using three pressure transducers.

3. Results and discussion

The comparison of aerial images from 2006 and 2012 reveals the development of several patterns and structures at the catchment surface (Fig. 2a). Whereas the image from 2006 shows a relatively homogeneous surface with structures resulting mainly from the construction process itself (e.g. caterpillar tracks, weir construction above the pond), in 2012 various vegetation patches are dominating the surface structure. First effects of surface and gully erosion processes were already visible in 2006. The 2006 image indicates that the structures left from the construction works triggered the initial channel network formed after heavy thunderstorms on the un-vegetated surface in spring and summer 2006. The further development of the gully network was clearly influenced differences of sediment properties between the western and the eastern part of the catchment. The overall stream length as derived from aerial images was higher in the western part compared to the eastern part (Fig. 2b). In both parts, the length of active erosion channels increased until 2007 and then decreased. The total area of the channel network was initially higher in the western part, but showed similar values for both parts in the following years. In 2007, the total area of the erosion channel network reached its peak, covering about 2 % of the surface catchment area. As a result, the ratio of stream length/stream area remained different for the two main parts throughout the years indicating that the gullies in the eastern part with dominating pure sandy substrate are wider and shallower, whereas in the western part with more loamy sands the channels are narrower but incised deeper. After 2007 specific plant species grew preferentially into erosion rills most probably due to better moisture availability and generally more favorable soil conditions of the sediments. Particularly common reed (*Phragmites australis* (Cav.) Trin. ex Steud.) was found in these linear structures. The invading vegetation stabilized surfaces and streambeds. Therefore, after 2010, the digitalization of gullies from aerial images was no longer possible due to increasing vegetation cover.

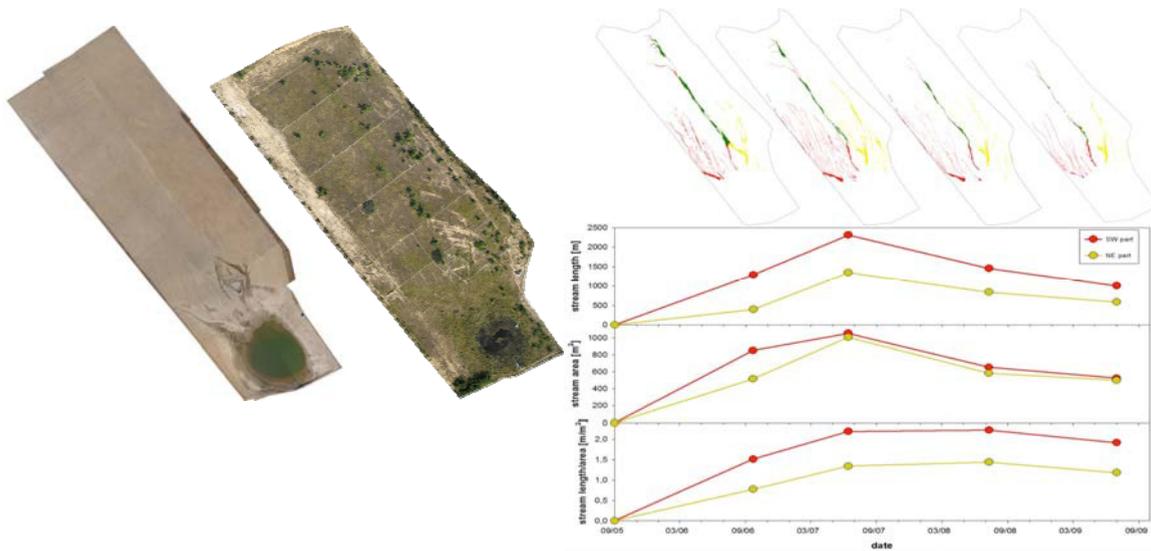


Fig. 2. (a) Comparison of aerial images of the 'Chicken Creek' catchment from micro drone pictures in September 2006 (top left) and September 2012 (top right); (b) Development of the active erosion channel network and derived length and area parameters (right)

Starting already during the construction period (2004/2005) precipitation accumulated on top of the aquiclude and formed a saturated zone in the sandy layer as a new structural hydrologic element of the catchment (Fig. 3). At the beginning of the monitoring measurements the groundwater table varied throughout the catchment between 0.3 m and 1.0 m above the clay layer. In the following years groundwater levels generally showed a clear seasonal pattern with higher levels in winter and decreasing levels in summer. Especially the very wet autumn 2010 resulted in raising groundwater levels close to the surface in the upper part of the catchment. After a decrease in summer 2011 groundwater levels remained high with seasonal fluctuations. The only exception to this trend was found for gauges close to erosion gullies in the lower part of the catchment (marked # in Fig. 3) that inclined deep enough to cut into the saturated zone so that groundwater could drain through these channels. These unexpected high groundwater levels may be explained by specific conditions caused by the dumping process during the construction of the site (cone-like subsurface structures of the aquifer sediments). The measured (vertical) saturated conductivity ($5 \times 10^{-6} - 5 \times 10^{-5} \text{ m s}^{-1}$) was lower than expected from the textural composition of the substrate, which again may be caused by sorting of the material during the dumping process. In addition, subsurface clay dams above the pond, which were constructed to direct groundwater flow to the central upper weir and to prevent downhill movement of the sandy substrates on top of the clay layer, obviously contributed to increased groundwater levels in the upper part of the catchment.

The pond filled very rapidly already few months after construction was finished (Fig. 4) mainly as the result of extreme weather conditions in the first winter 2005/06 (high snowfall, runoff of melting waters on frozen soil surfaces). The fast reaction of the pond level to precipitation events indicates that surface runoff is still the dominating input flux to the pond. Both water table rises in the pond and discharge at the weir occurred during or immediately after precipitation or snowmelt events. During dry periods with high evaporation, the pond level declined indicating that groundwater inflow during these periods is lower than evaporation losses from the pond surface.

Output from the discharge weir was detected for the first time at the beginning of 2007, almost 1.5 years after construction was completed (Fig. 4). Discharge remained quite episodic following precipitation events in 2007 – 2009. Only then discharge started to be more continuous except for drought periods in summer. Total discharge from the catchment considerably increased over the subsequent years accounting for 14.0 % of total precipitation inputs in 2007, 12.2 % in 2008, and 19.7 % in 2009. In the extremely wet year 2010 total discharge almost equalled precipitation (95.7 %).

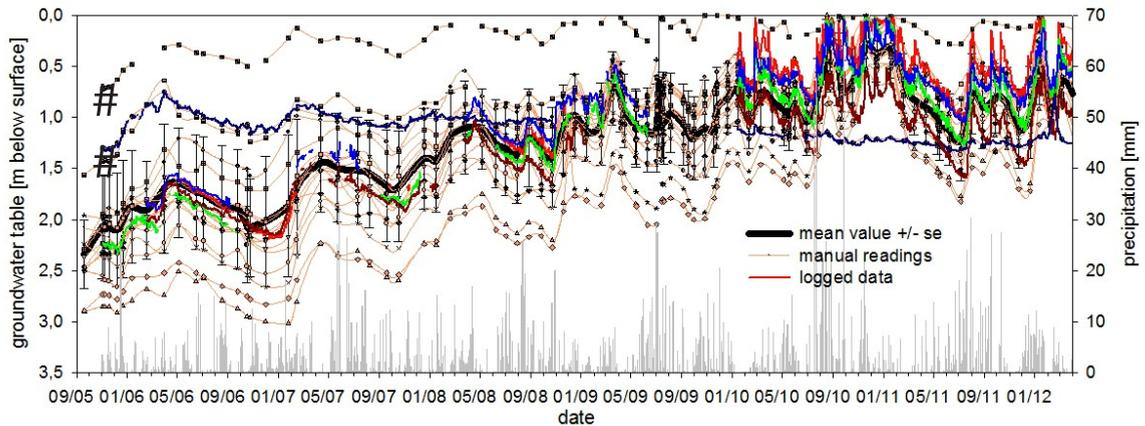


Fig. 3. Groundwater levels below surface at 17 sites throughout the catchment (cf. Fig. 1b; symbols mark groundwater gauges with manual readings, lines are gauges with logged readings; mean \pm se gives the mean value of all gauges with error bars indicating standard error (se); # marks the two gauges draining groundwater mentioned in the text)

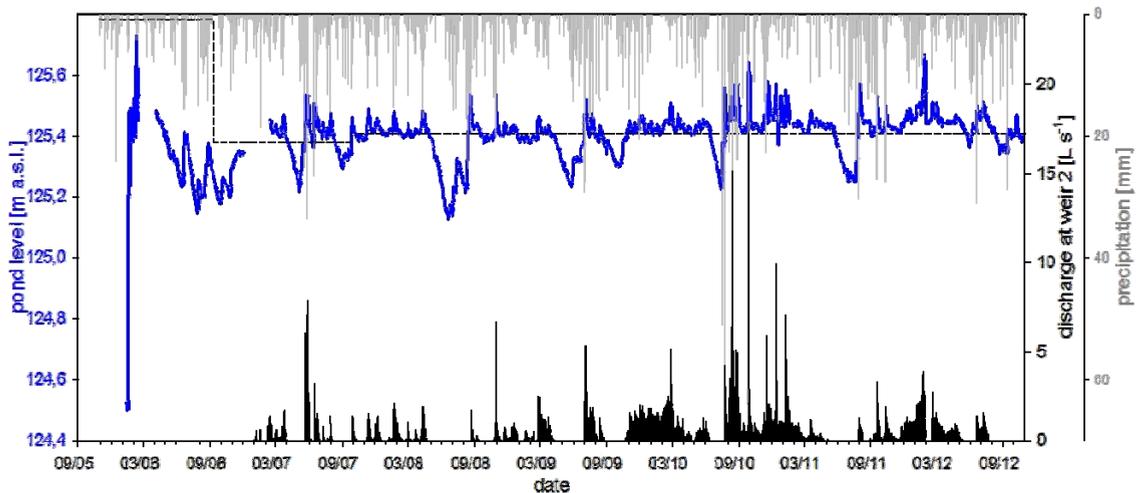


Fig. 4. Water level of the pond (blue line), discharge from the catchment (black bars) and daily precipitation (grey bars); the dashed line indicates the level of the pond outlet that was lowered in 2006 due to weir reconstruction

These data indicate that during the initial years surface runoff processes dominated catchment hydrology inducing severe surface and gully erosion. At the same time, groundwater built up on top of the aquiclude to very high levels increasing the storage within the catchment. The special meteorological conditions in 2010 finally led to an almost complete saturation of the sediment body. Surface runoff and

gully runoff that also drained the groundwater then resulted in high discharge rates (41.9 % and 38.6 % of precipitation in 2011 and 2012, respectively).

During the initial development, the overall vascular plant cover increased substantially. In 2009, it reached a temporary peak value of 38.5 %. The total number of vascular plant species increased quite continuously from 18 in 2005 to 155 in 2012. Woody plant species were increased from one in 2005 (the nitrogen-fixing *Robinia pseudoacacia* L.) to 14 in 2010. Steadiness was highest for *Pinus sylvestris* L. (32 % in 2010 and 37 % in 2011). However, *R. pseudoacacia* was the structurally dominant tree (steadiness 13 % in 2010 and 19 % in 2011). In summer 2012, a survey of tree species revealed 17 species with 4000 individuals with a height > 0.5 m, mainly in the lower part around the pond and in the eastern part of the hillslope. Besides *R. pseudoacacia*, other nitrogen-fixing plant species rapidly became a major component of the establishing vegetation. In 2007, Fabaceae (legumes) covers were significantly higher on plots in the western part. In 2009, legumes cover was dense throughout the catchment. In 2010, a general decline in legume cover was observed, but more pronounced in the western part resulting in a changed dominance pattern. Also the number of Fabaceae species developed in accordance with the west-east cover pattern. In the eastern part species numbers increased moderately (2, 4, 8, 8, 10, 11 species in the years 2006 - 2011, respectively) compared to the initially stronger increase in the western part (0, 7, 10, 12, 11, 15 species in the years 2006 - 2011, respectively). Thus, the example of Fabaceae clearly demonstrates that, due to differing substrate properties in the two parts of the catchment (i.e. water holding capacity, cation exchange capacity), the processes of colonization and space occupation were asynchronous (Fig. 5).

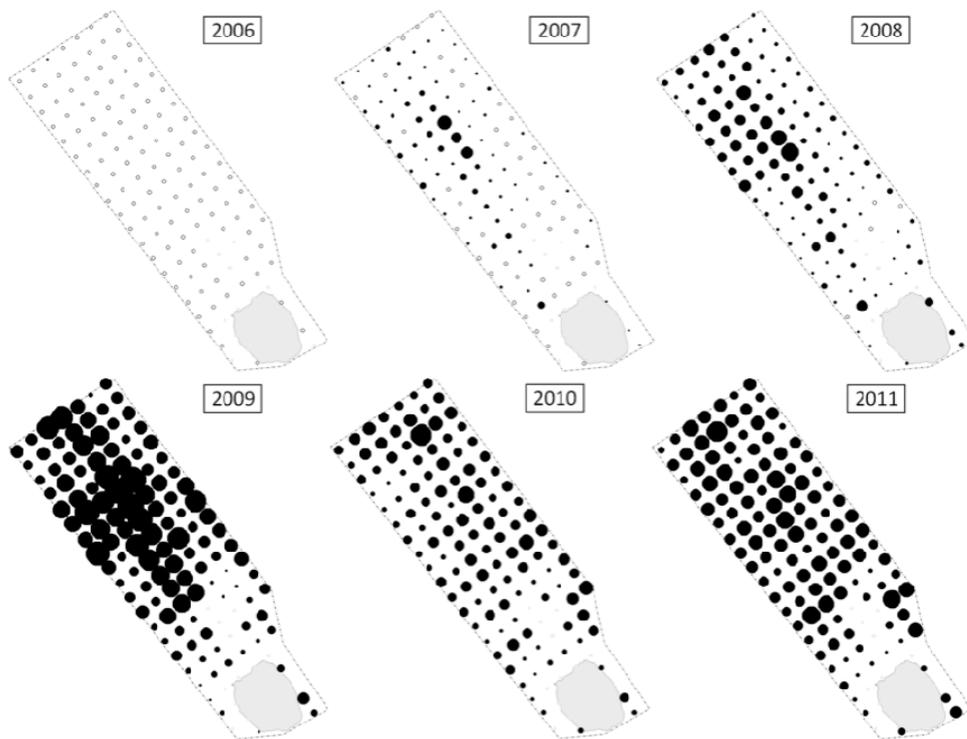


Fig. 5. Distribution and cover of all legumes from 2006 to 2011 within the catchment. Size of the dots depict cover classes: ≤ 0.1 %; $> 0.1 - 0.5$ %; $> 0.5 - 1$ %; $> 1 - 2$ % in 1 % steps up to 10 %; in 5 % steps up to 80 %

The decline in total vascular species cover in 2010 was driven by the marked downturn of the single species *Trifolium arvense* L. – which was by far dominant that time. A similar dependency in total cover on one leguminous species has also been reported from Mount St. Helens (USA), where vegetation cover initially increased, but then fluctuated due to changes in the cover of the legume *Lupinus lepidus* Douglas ex Lindl [11]. Both systems at an early succession stage were obviously limited in their offsetting abilities and hence showed low resilience. Whereas at the beginning of succession individual numbers of species were low, later the number of species and especially the number of individuals per species increased. We expect that this will result in the ability to compensate for single species cover losses in future development. The extensive and simultaneous diminution of a single plant species over a larger area can be defined as subunits of succession stages [12]. Accordingly, a high level of spatial homogeneity in the cover of a single species followed by significant divergence (not necessarily an overall decline) can be regarded as a characteristic feature of early succession.

During the first seven years, we observed considerable changes within the catchment, some of them were unpredicted or unexpected, at least in its rate of development, e.g. the fast establishment of a very large number of plant species, the formation of a large saturated zone or the high extent of surface runoff in the early stage. Both internal and external factors could be identified as driving forces for the formation of structures and patterns in the artificial catchment. Initial structures formed by the construction process (e.g. catchment morphology, subsurface structures like clay dams and dumping cones, caterpillar tracks on the surface) and initial substrate characteristics (e.g. texture, geochemistry) were decisive both for the distribution and flow of precipitation water and for vegetation succession. External factors like episodic events (e.g. heavy thunderstorms) triggered erosion and dissection during this initial phase, and were largely promoted by the low vegetation cover and the unconsolidated sandy substrate. These processes resulted in the formation of new structural elements like gullies and channels and sedimentation areas. During this initial phase, internal factors imposed by the construction and design of the catchment clearly dominated processes. As a result, we observed an overall differentiation of the site, e.g. with respect to water availability and texture redistribution, into areas with abrasion or accumulation processes dominating and areas with stable surfaces. External factors like the restoration activities around the catchment influenced the development of the site. For example, besides the initial soil seed bank [10], the surrounding environment of the catchment clearly affected species invasion [13], e.g. by anemo- and zoochory. The dissection and stability of surfaces may be an important factor for the establishment of plants and habitats as well as for the formation of vegetation patterns and biological soil crusts. However, also after seven years, certain areas of the catchment still remained free of vegetation. We assume that sediments in former erosion gullies offer better site conditions for plants in terms of water (and nutrient) availability, so that vegetation establishment preferentially started along these linear structures.

The transformation of the initial geo-system into areas with evolving terrestrial or aquatic characteristics and from a very episodic to a more permanent stream network and discharge, together with the observed vegetation dynamics increased site diversity and heterogeneity with respect to water and nutrient availability and transformation processes compared to the more homogenous conditions at point zero. We expect that these more permanent structures and patterns established after seven years will greatly influence the future development of the catchment with respect to e.g. input and accumulation of soil organic matter, nitrogen input and availability by symbiotic microbial N-fixation, development of root systems and soil food webs, weathering and soil formation, element cycling, and the water and element budget at the catchment scale.

Furthermore, we expect that feedback mechanisms between the abiotic and biotic components will intensify with the number of effective structures in the system. For example, the increasing density of plant cover will certainly affect the further groundwater development, as transpiration rates will significantly increase. This should affect the observed trend of increasing groundwater tables towards

more pronounced seasonal fluctuations, which in turn may have consequences for the composition of the vegetation cover. The vegetation itself will increasingly determine its immediate surroundings, e.g. species-specific negative plant soil-feedbacks are suggested to gain importance [14] and might already be an important mechanism underlying the dramatic dynamics of *T. arvense* [15]. The focus of further investigation therefore will concentrate on these feedback loops.

4. Conclusions

Our results on the initial development of an artificial catchment underline high dynamics in the differentiation of newly exposed land surfaces [16]. The processes and feedback mechanisms in the initial development of a new landscape may deviate in rates, intensity and dominance from those known from mature ecosystems. It is therefore crucial to understand these early phases of ecosystem development and to disentangle the increasingly complex interactions between the evolving terrestrial and aquatic, biotic and abiotic compartments of the system. Most time series of the monitoring reflect the strong influence of initial system structures (internal effects) and of stress events in the very early phase (external effects) on system development. The compounding effect of such early initial structures or pulses may be of higher relevance for the understanding and modeling of such systems than all later system attributes. While in later phases external effects may modify system development continuously, steadily and slowly, early structures and events may lead to chaotic system development and bifurcations, e.g., in the water drainage, soil erosion, or vegetation spread trajectories. Improved understanding, modeling and predictions of system behavior in such unstable phases require both a detailed monitoring of system development as well as of internal and external drivers. A better knowledge of dynamic changes and the role of spatial and temporal patterns in the early stage of development is also of practical relevance for restoration measures and contributes to the growing field of restoration ecology (*sensu* [17-20]).

Chemical and biological data of the pond (not shown) revealed that pond succession was clearly affected by the changes in its catchment, but also an increasing importance of internal processes [8].

The synopsis of the data reveals the crucial role of the initial system structure at point zero and any events like heavy rain, storm or abrupt snow melting for the pattern and processes in the following geo-phase of the system. Initial structures and events trigger a long-lasting compounding effect on nearly all monitored time series. Due to their overwhelming effects future research should strive for an even better recording of initial internal system traits and external drivers. A specifically designed variation of initial structures and external events might clarify their important role in temperate ecosystems.

Compared with tropical and arid systems the temperate ecosystems we analyzed represent a medium period length from point zero to continuous vegetation coverage. The slower the vegetation development and the more frequent external events as cloudburst, sandstorms, or drought periods, the more relevant and lasting become the system traits in the very early stage of the system. Implications of this understanding of initial ecosystem development could be e.g. improved forecasting ecosystem behavior, stability and functioning using models. The effect of surface crusting on infiltration and surface runoff, the buffer effect of the pond zone, and the effect of dumped belowground sediment structures were identified as main problems in modeling this comparably simple system. In addition, the applicability of pedo-transfer functions derived from natural soils may be problematic in the early phase of soil development. Therefore, long-term monitoring of initial ecosystems may provide important data and parameters on processes and the crucial role of spatial and temporal structures and patterns to solve these problems. Artificially created catchments could be a suitable tool to study these initial developments at the landscape scale under known, designed and defined boundary conditions.

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