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Dynamics of initial ecosystem development at the artificial catchment Chicken Creek, Lusatia, Germany

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Abstract

In autumn 2005 the artificial catchment Chicken Creek was completed in an open-cast lignite mine in Lusatia, Germany. The 6 ha area has been constructed as a two-layer system consisting of a clay aquiclude and a sandy aquifer at the top. After construction the site was left to an unrestricted and unmanaged succession. A comprehensive environmental monitoring program started immediately after the site was completed. Time series of essential environmental parameters were recorded with high temporal and spatial resolution. This paper presents selected time series of the past six-year ecosystem development. Important changes registered in this period allow for the definition of distinctive phases of the still ongoing initial ecosystem evolution. A primary, short but pronounced geo-phase – characterized by surface runoff, excessive erosion and sedimentation as well as very rapid immigration of biota – was followed by a hydrological dominated phase with processes such as groundwater recharge. At the end of the study period biotic processes became more evident. It can be concluded that the artificial catchment offers unique opportunities for interdisciplinary research on the establishment of an ecological system with rapidly growing complexity. The highly dynamic development of the Chicken Creek catchment provides the possibility to observe manifold changes within short time and to detect feedbacks and their modifications between different ecosystem compartments.

Keywords

initial stage, environmental monitoring, erosion, groundwater recharge, soil development, primary succession

1. Introduction

Watersheds as the only landscape unit with naturally defined boundaries are often used in interdisciplinary ecological studies for very different purposes and at different scales. Prominent examples for large-scale ecological research are the Hubbard Brook Experimental Forest (Campbell et al. 2007) or the Walnut Gulch Experimental Watershed (Stone et al. 2008). Both sites are naturally developed catchments observed to understand the ecological response of forest ecosystems to various disturbances and manipulations or rainfall-runoff processes, respectively. In Germany, e.g., hydrological research in the Schäfertal catchment already started in the 1960ies (Reinstorf et al. 2013). Generally, the number of instrumented watersheds worldwide is large and it is still growing, as the problem of global change is often investigated using such experimental landscape units. Whereas many of these sites deal with specific disciplinary, often hydrological oriented objectives, interdisciplinary approaches are of growing importance. Lin (2011) pointed out that “processes occurring at and near the Earth’s surface do not operate independently”. In his opinion recently postulated new sub disciplines of hydrology such as hydropedology, ecohydrology or hydrogravimetry are of increasing importance as they clearly demand the interdisciplinary exchange with other areas of ecological research and geosciences.

Such multidisciplinary approaches are the background for recently established networks such as the Critical Zone Exploration Network in the USA (Brantley et al. 2006). In Germany a network of terrestrial environmental observatories (TERENO) was launched in 2008 (Bogena et al. 2012, Zacharias et al. 2011). Another example for interdisciplinary catchment research is the Water & Earth Science Competence Cluster (WESS) considering several different catchments of different scales in Germany (Grathwohl et al. 2013). In TERENO, long-term integrated observation platforms are operated as a joint research network activity between several institutes of the Helmholtz-Association and in close cooperation with university partner institutions with the aim to investigate consequences of global change for terrestrial landscapes and ecosystems. Measured data from the TERENO sites are provided by the TEODOOR portal (Kunkel et al. 2013). Regional “terrestrial observatories” have been established in four regions, selected to provide a representative cross-section of bio-geo-climatic zones with high vulnerability to climate change effects in Germany, by integrating existing research stations and activities and complementing them with dedicated new infrastructure for long-term integrated environmental monitoring and observation. The TERENO Northeast German Lowland Observatory (Bens et al. 2012) has been established in close vicinity to the artificial catchment Chicken Creek. These investigations are also based on catchments as spatial units. However, the expected response of the monitored ecosystems to global change processes is supposed to be very subtle and difficult to observe in the short term.

In contrast, highly dynamic conditions are found when investigating ecosystems in their initial state of development. This initial stage can be defined as the time period between the start of ecosystem development ("point zero") and the quantitative establishment of a first dynamic equilibrium of element cycling of an ecosystem (Schaaf et al. 2011). The duration of this initial stage differs with the type of ecosystem and, for example, climatic conditions. According to Schaaf et al. (2011), the initial stage can be characterized as a sequence of development phases taking into account that the number of ecosystem patterns and related structural complexity are growing with ecosystem development. This assumption is consistent with ecosystem development models, e.g., provided by Odum (1969), or more recently discussed by Fath et al. (2004). In most cases such initial systems are far less structured and less heterogeneous than mature systems (e.g., Huggenberger et al. 2013) which have undergone an evolution of several centuries or millennia. During ecosystem development both the complexity of structures and their interactions increases as additional patterns (e.g., surface and subsurface flow paths, humus layers and soil horizons, rooting channels and worm burrows) and processes (e.g., erosion and sedimentation, C-accumulation and pedogenesis, effects of biota) appear. These initial processes determine and control evolving properties and functions of the system (Schaaf et al. 2011). Thus, the analysis of young ecosystems in their initial stage of development seems to be a fundamental approach and essential requirement to disentangle the complex web of processes, and help to better understand both ecosystem functioning as well as ecosystem reactions to alterations of structural properties. Interactions between newly emerging structures and related processes, including feedback processes between existing and new structures, should be much more visible if initial ecosystems are investigated.

The objective of this paper is, therefore, to introduce a promising scientific method and a category of watersheds, which is supplemental to approaches such as TERENO – the specific use of artificial catchments with evolving initial ecosystems. Prominent examples for other artificial watersheds are Hydrohill in China (Kendall et al. 2001) or the Biosphere 2 project in Arizona, USA (Hopp et al. 2009) with clearly disciplinary, but mostly hydrological, emphases. This paper presents a unique new research site that has been launched for interdisciplinary ecological research in autumn 2005. The artificial catchment Chicken Creek (the German name is “Hühnerwasser”) offers the opportunity to investigate linkages between abiotic site development and biotic responses and vice versa in a well-defined, constructed system at the landscape scale. The evolution of such initial ecosystems is rapid and highly dynamic so that short-term feedback processes and changes of ecosystem behavior can be studied directly. The main focus of the Chicken Creek project is on the multidisciplinary study of ecosystem and landscape functioning (Gerwin et al. 2011). Thus, the project addresses the problem of co-evolution of ecosystems and landscapes which had been postulated as one of the central questions of ecosystem research (Reinhardt et al. 2010).

The Chicken Creek catchment is equipped with a comprehensive ecological monitoring network observing hydrological, pedological, limnological and biological compounds and processes. In this paper results of the first more than six years of intensive monitoring of ecosystem evolution in the Chicken Creek catchment are presented demonstrating the dynamic evolution of the system as well as the occurrence of first feedback processes. Time series of geomorphic, hydrologic, soil and water chemistry as well as biotic parameters have been recorded in high temporal and spatial resolution. The different monitored components are discussed as parts of the developing system as a whole and already existing and evident feedback controls between single compartments are presented.

2. Artificial catchment and monitoring program

2.1 Artificial catchment

The Chicken Creek catchment was constructed as part of the post-mining landscape of the Lusatian lignite mine Welzow-Süd in the State of Brandenburg, in Northeast Germany, about 150 km southeast from Berlin (Fig. 1). The site was built as the headwater of a small stream of the same name and consists of an area with clear boundary conditions at the surface and in the underground and has both terrestrial and aquatic parts. Detailed descriptions of its internal structures and also of the construction works are summarized by Gerwin et al. (2009, 2010 and 2011); the most important properties are introduced below.

Generally, the site is constructed as a two-layer system with a clay layer as the aquiclude and an overlying sandy layer as the aquifer. The watershed covers an area of 6 ha (see Fig. 2 for site dimensions and inner structures). As a unique feature this site was left to an unrestricted and unmanaged succession after the construction work was completed in 2005. Faunistic and floristic patterns are allowed to evolve according to the initial site conditions, which are also subject to natural modifications during the further ecosystem development. Generally, the site can be divided into three major sections: (i) the backslope area, (ii) the footslope, and (iii) the pond basin. A subsurface clay dam in the footslope area was constructed as a barrier for groundwater fluxes and for geo-mechanical reasons. The site is completely fenced off to avoid disturbances by human visitors or the abundant game animals.

2.2 Ecosystem monitoring

A comprehensive description of the monitoring configuration and methods in use as well as of preliminary results can be found in previous “Ecosystem Development” publications by Gerwin et al. (2010), Schaaf et al. (2010) and Elmer et al. (2011) (the volumes of this project series are available online via their URN given in the list of references). Basic monitoring installations - such as groundwater gauges, atmospheric deposition samplers, soil moisture probes - are oriented along a regular network of grid points, which were defined at the start of observations in autumn 2005. Several new measuring devices were installed during the following years at evolving structures of the system which are of specific interest (weirs and flumes for runoff measurement in erosion gullies, additional groundwater gauges). In this paper results of the following monitoring investigations are introduced.

2.2.1 Meteorology

Two weather stations operate in the catchment. Weather station 1 is used for the registration of basic data, whereas weather station 2 provides more detailed data. Data obtained at station 1 are presented here. This station measures basic meteorological parameters with time resolution of one hour since September 2005 and is located in the upper eastern part of the catchment. Details of the installed techniques are published by Biemelt and Nenov (2010). Measured annual precipitation and average temperature values as well as long term data for comparison are given in Tab. 1.

2.2.2 Remote sensing

A micro drone (MD4-200, microdrones GmbH) equipped with a digital camera is in use to take aerial photographs of the whole catchment with a high spatial resolution (terrain resolution of 3 cm x 3 cm). Photographs have been taken regularly in spring (April), summer (June/July) and autumn (September). Technical details of the drone and details of picture processing are published by Veste et al. (2010). The aerial photographs together with digital elevation models (DEMs provided by Vattenfall Europe Mining AG) are used to identify and quantify surface structures such as erosion rills or vegetation cover. The vegetation cover within the catchment was calculated on the basis of these aerial photographs using ArcGIS (ESRI, version 9.3). A supervised classification was conducted to identify areas with vegetation cover. To calculate the vegetation cover within the erosion rills, these maps were superimposed with maps of the gully network, which were also derived from aerial photographs.

2.2.3 Hydrology

A total of 30 groundwater gauges are installed in the catchment area. Nine of them register groundwater levels automatically; the levels at the other gauges are measured manually every two weeks. Biemelt et al. (2010) describes details of the measuring arrangement. Within three larger erosion rills, flumes were installed to measure surface runoff. In this paper data from the central erosion gully are presented, which provides the streambed for the most important stream of the site. Permanent base flow is found here in the lower parts whereas periodic peak flow occurs after heavy rainfall events. The measuring techniques used in this gully to quantify runoff (“flume 2”: stainless steel H-flume made by Umwelt-Geräte-Technik GmbH) are described by Biemelt et al. (2010). The same holds true for the subsurface drainage gutter, measuring the baseflow in the main eastern gully since June 2009. Two weirs are operating within the catchment: The inflow to the pond from the artificial spring area (Fig. 2) is determined by means of weir 1 (upper weir), whereas total catchment runoff is measured at the outlet of the pond by means of weir 2 (lower weir). The discharge from the pond is controlled by its water level, which is automatically recorded by two pressure transducers.

2.2.4 Water and soil solution chemistry

Bulk aerial deposition was sampled initially at 18 grid points. Since the data of bulk precipitation and rainwater composition showed no consistent spatial trend over the catchment area, sampling points were reduced to 9 in November 2009 (Schaaf and Elmer 2011). Both weirs and the flume in the central gully were equipped with automated water sampling units (ISCO 6712, ISCO 3700). Daily water samples were taken and collected every two weeks. Sampling started in June 2007 at both weirs and in May 2008 at the flume. Daily samples were measured for pH and electrical conductivity (EC) and biweekly mixed samples were used for further analysis. Soil solution was sampled from four permanent soil pits from October 2007 in two depths (30 cm, 80 cm) using boron silicate glass suction plates (∅ 10 cm) with permanent pressure of -10 kPa. Samples were taken every two weeks. All solution samples were analyzed for pH (Beckmann pH34 glass electrode and WTW pH537) and electrical conductivity (EC; Hanna HI 8733 and WTW LF537), concentrations of cations (ICP-OES Unicam 701 and Thermo Scientific iCAP 6000), anions (IC Dionex 5000), NH_4 (Rapid Flow Analyzer Alpkem), DOC, TOC, TIC and TN (Shimadzu TOC-5000 and VCPH+TNM-1).

2.2.5 Vegetation

Since 2005, the developing vegetation of the study site has been recorded in July and August each year. Assessment plots are assigned to the regular grid (20 m x 20 m). Each grid point is permanently marked by a flag denoting the centre of a quadrate plot of 25 m², with additional plots of 1 m² at each corner. The monitoring program is, therefore, based on a nested plot design with one 25 m² plot at each grid point including four 1 m² plots (Zaplata et al. 2010).

2.2.6 Soil fauna

Sampling of soil fauna began in October 2005, and from then on has taken place at usual times of peak abundances of the soil fauna, namely in April/May and October. A total of 27 soil cores for both microfauna (Nematoda, Tardigrada) and mesofauna (Collembola, Acari) were taken on the respective sampling dates. Soil cores for microfauna (3.5 cm in diameter) and mesofauna (6.4 cm in diameter) were always taken to a depth of 5 cm and directly adjacent to one another (Elmer et al. 2010). The “weighted faunal analysis” concept was applied, where functional guilds of nematodes are indicators of food web complexity and nutritional status of the post-mining soils (Hohberg 2003).

3. Time series of ecosystem development

3.1 Geomorphic development

During the first two years (until 2007), development of the Chicken Creek catchment was dominated by intensive surface runoff processes, e.g., after episodic heavy precipitation events or snow melt, resulting in severe sheet and gully erosion causing considerable changes of the initial surface structure. Visual observations in the first years also indicated a noticeable contribution of wind erosion to the total sediment balance. Wind erosion modeling and aerial image analysis suggested that aeolian sediment relocation was about two magnitudes lower than that caused by water erosion (Maurer and Gerke 2011). Further hydro-geomorphic development was characterized by an increasing vertical incision and lateral extension of the gully network. Width and depth of these channels were highly influenced by the varying textural composition of the initial substrate. As a consequence, overall length and area of active streambeds within erosion rills increased rapidly until mid of 2007 (Fig. 3). Sediment relocation and the emergence of erosional and depositional structures resulted in rapid surface differentiation.

Biological colonization of the site started immediately and became obvious in 2009 when the vegetation cover rapidly increased to more than 30 % (Fig. 7). This development changed geomorphic development clearly. After the first phase of rapid growth and vertical incision, the general evolution of the erosion rill network was apparently completed and the prevailing processes changed. With the development of biological soil crusts (Fischer et al. 2010, Spröte et al. 2010) and an increasingly denser vegetation cover the growth of the rill length and stream bed area was disrupted and both length and area of actively eroding rills decreased. This corresponds to the establishment of vegetation in formerly more unstable regions in combination with vegetation growing preferably along the former stream beds within the rills. In fact, plants started invading notably into the erosion rills (Fig. 4) and it is assumed that they could benefit from the sediment structures formed by the ephemeral small streams. As a consequence, the erosion gullies became paths of vegetation dispersal for some species that had been immigrated early to these structures. Once the vegetation cover reached high values in 2010 and 2011, the analysis of stream length and area using aerial photographs was no longer possible.

The Chicken Creek catchment offers the unique opportunity to investigate the influence of developing structures in the terrestrial parts of an initial ecosystem on a young aquatic system. The described geomorphic development in the terrestrial part of the catchment is mirrored by the evolution of an extensive sediment body in the pond basin during the first years of development, which reduced depth and volume of the pond and increased turbidity. Longer rainy periods and episodic precipitation events contributed to an enhanced material input as revealed by the annual sedimentation rate of up to 30 cm yr^{-1} in the inflow area of the pond. Hence, already in 2008 19.7 % of the original pond volume was filled with sediments from the catchment (Kleeberg et al. 2010) and a pronounced alluvial fan established in the inflow region of the pond. In the following years, sediment transport into the pond was considerably reduced as shown by measurements of the sediment structures in the pond in 2010 and 2011. Sedimentation traps revealed that most sediment was retained by the growing reed belt around the pond and the sedimentation rate decreased to about 17 cm yr^{-1} (Kleeberg 2011).

3.2 Hydrologic development

Surface runoff and the primary groundwater recharge were the most important hydrologic processes during the first stage of development of the catchment

(Mazur et al. 2011). Substrate saturation and the establishment of a groundwater body above the clay layer proceeded over several years. This groundwater recharge period between 2005 and 2009 is defined by a trend of increasing groundwater levels overlain by typical seasonal fluctuations due to prevailing natural discharge and recharge processes in summer and winter, respectively (Fig. 5). This period of groundwater filling was apparently completed in 2009 when the overall increasing trend of the groundwater table ended and only the seasonal fluctuations remained. However, exceptional high amounts of rainfall in 2010 led to a temporary increase of groundwater levels up to the surface, indicating the almost complete saturation of the sediment body. In contrast, in 2011 with "normal" precipitation amounts, groundwater tables declined again to the level of 2009 when the equilibrium between discharge and recharge was reached for the first time.

The amount of runoff registered in the two main erosion gullies increased over the observation period, particularly visible at the central erosion gully as shown in Fig. 5. A constant but relatively low base flow has been observed in both streams since 2007 and has been measured since 2008. As of 2010 a marked increase in runoff with pronounced peaks after rainfall events was detected.

The pond integrates most of the hydrological processes occurring in the terrestrial parts of the system. A close relationship between the temporal patterns of rainfall and discharge at the pond weir (Fig. 5) demonstrates the still initial conditions of the catchment: With very short delay, the pond level increases after rainfall starts. The very sudden, complete filling of the pond basin with water in winter 2005/06 was the result of specific meteorological conditions demonstrating the importance of surface runoff in this initial system: Melting snow combined with rainfall on frozen soil led to very high surface runoff into the basin. Even if this extraordinary event was promoted by the bare sediment surface, physical soil crusting and the described weather conditions, the importance of surface runoff with regard to the hydrological behavior of the catchment is still obvious. Large amounts of water from precipitation still directly flow into the pond, causing sudden changes of the pond level. In August 2010, permanent discharge from the pond was observed due to high water levels caused by large amounts of precipitation. The inflow into the pond reached significantly higher values and showed higher temporal dynamics compared to the outflow measurements. The pond storage attenuated these high dynamics, which produced a smoother curve of pond discharge.

3.3 Chemical development

Chemical composition of surface runoff, pond water and soil solutions in the catchment changed dynamically over time (Fig. 6). With time, concentrations and EC values of the soil solution corresponded well to the chemistry of runoff waters with similar temporal trends. The highest EC values and highest element concentrations were found in the surface runoff sampled in the central erosion gully.

Due to the carbonate content of the substrates, mean pH values varied between 7.0 and 8.4 in all water and soil solution samples. The parallel decreases of SO_4 as well as of Ca and Mg (both not shown here) are clearly reflected in the electrical conductivity (EC). Traces of gypsum in the substrates may be a source for both Ca and SO_4 in the initial phase of leaching. Since the gypsum contents were very low, decreasing sulfate concentrations in both soil water and pond water indicated that gypsum was dissolved and mobilized within a few years. The occurrence of gypsum in the Pleistocene substrates can be attributed to very high atmospheric deposition of both sulfur and alkaline ashes from unfiltered lignite-fired power plants in the former German Democratic Republic (GDR) together with low precipitation and leaching (Dultz and Kühn 2005). With increasing vegetation cover and litter input to the soil, carbonate weathering increased as indicated by increasing inorganic carbon (TIC) concentrations and was the main control for calcium concentrations in soil solution. With regard to water chemistry of the upper weir and flume samples, concentrations decreased significantly, mainly for calcium, magnesium and sulfate, whereas bicarbonate increased. The overall concentrations at the flume and the upper weir were much higher compared to soil solutions and pond water at the lower weir.

The element budgets were strongly influenced by both changes in water chemistry and in discharge rates mentioned above. Whereas the concentrations found in bulk deposition (values for “precipitation” in Fig. 6) were low and did not vary much over the years, output rates increased over the observation period mainly as a consequence of the strong increases in discharge, especially in the very wet year 2010. In all years, the catchment was a strong source for calcium, magnesium, sulfur and inorganic carbon. In contrast, the catchment acted as a strong sink for nitrogen as was expected for strongly nitrogen limited systems.

3.4 Biotic development

The initial spatial differentiation of substrate characteristics led to an early patterning of species composition particularly with regard to spatial differences in vegetation cover. For instance, the first dominating plant species *Conyza canadensis* colonized the whole catchment but differences in cover reflected the subareas of the catchment (Zaplata et al. 2011). During the first years a first differentiation in species composition occurred, mainly reflecting the parts of the catchment area consisting of slightly different substrates. Furthermore, some plant species are mainly restricted to the area close to the pond, where an increasingly broader reed belt (*Phragmites australis*) has its origin.

Total plant cover increased substantially and reached a preliminary maximum in 2009 (Fig. 7). Parallel to this trend, groundwater reached its maximum level facilitating water supply also for shallower rooting plants. A general decline in vegetation cover was then observed in 2010, mainly caused by a decreasing cover of the dominant species *Trifolium arvense*. Possible reasons for this decline are unfavorable weather conditions with a harsh winter season 2009/2010, characterized by a long-lasting frost season and large amounts of snow, and extremely high rainfall amounts during summer 2010. Further, this phenomenon illustrates the large dynamics of plant populations (Zaplata et al. 2013) and the low overall resilience in this developmental state. In 2011 the total cover again reached almost the level of 2009. At the same time, the importance of woody plants is increasing. Most important is the leguminous tree species *Robinia pseudoacacia* which rapidly colonizes the catchment area. Generally, nitrogen-fixing plant species became a major component of the establishing vegetation. The importance of this plant functional type for early ecosystem developmental states is clearly reflected by their comparatively high cover, especially from 2009 on. Parallel to the increase of vascular plants the cover of mosses has been rapidly growing since 2009/2010, most probably favored by the wet weather conditions in 2010.

The total number of vascular plant species increased quite continuously (Fig. 7). This increase was particularly rapid from 2005 (about two months after final surface flattening) to 2006. Despite the still ongoing immigration, the increase of total species numbers has slowed down. For instance, between 2010 and 2011 the total number of vascular plants only grew by one additional species. However, species turnover is not shown here, as presented numbers account for the net balance and hence the sum of immigration and extinction.

The floristic colonization of the Chicken Creek pond was investigated by Lessmann and Nixdorf (2011). They found a high species richness of phytoplankton within a few years. Submerged macrophyte biomass, however, soon exceeded phytoplankton biomass. According to their results phytoplankton was characterized by a low number of steady taxa indicating a generally low stability of the community. In addition, a sharp increase in phytoplankton biomass occurred in 2010, one year after the increase of terrestrial vegetation cover.

One month after construction in autumn 2005, the initial substrates were already inhabited by first representatives of the soil food web (Fig. 7). Specimens of those first and later colonizing species found favorable conditions and nutrient resources sufficiently available to survive in the newly formed substrate, and from there some pioneer species spread almost immediately into individual-rich populations (Russell et al. 2010). Still numbers of overall soil animals were low during the first two years of succession. As of 2007, densities steadily increased and slowly reached numbers determined for mature soils. Overall species numbers, on the other hand, were still relatively low in the sixth year of catchment development and many more species are expected to arrive and settle in the future. None of the soil faunal groups under investigation have yet reached their usual species numbers, except for tardigrades, which already passed their peak in 2009.

The basal status of the Chicken Creek communities is mirrored by the faunal profile presented in Fig. 8. It suggests that the flow of resources into the food web system as well as the prevalence and abundance of higher trophic level organisms was dramatically low in 2005. By 2007, the number of trophic links within the soil food web increased substantially and in October 2009 and October 2010 reached structure indices determined from mature, undisturbed soil food webs (Fig. 8, dark green dots, quadrat C). This concurs with the vegetation becoming more diverse and the plant cover rising, thus providing an increasing supply of nutrient resources and niches. In accordance with the distinct increase of plant cover in 2009, plant associated biota (e.g., root-feeding nematodes) are positively correlated with the above-ground succession. Hence, the soil food web clearly developed in association with the plant community, which is typical for the initial stage of succession (Bardgett and Wardle 2010). Densities and species richness of soil-inhabiting carnivores, on the other hand, remained rather low throughout the first six years of ecosystem development and established populations were not found until 2009.

4. Phases of ecosystem development

Ecosystem development comprises a series of transitions and changes in environmental conditions, which again affect biological colonization. These changes may be caused by varying external factors and/or may be controlled by internal processes (Begon et al. 2005). During the first six years considerable changes were observed within the Chicken Creek catchment. Both internal and external factors could be identified as driving forces of new structures and patterns. It is hypothesized that the very first phase of ecosystem development is characterized by a still more or less abiotic system developing under the influence of existing structures and external drivers (Schaaf et al. 2011). This is in good accordance with the observed course of ecosystem development in the artificial catchment Chicken Creek.

Most of the time series of ecological parameters registered at the Chicken Creek catchment indicate distinct temporal trends. Some of them reveal that processes have already reached their maximum whereas others are still at their beginning. Different phases in the initial ecosystem development at Chicken Creek catchment can be distinguished and defined preliminary as follows and summarized in Fig. 9. Phase I was characterized by a very rapid alteration of surface structures by geomorphic processes, particularly erosion and sedimentation. Simultaneously, pioneering biota invaded the site forming early, irregular patterns of scattered populations. Since the catchment is situated within a large post-mining area, surrounding sites are characterized by different types of ruderal vegetation, but also initially restored agricultural (e.g., lucerne) or afforested sites (e.g., black locust, pine, oak) that may have served as sources for the starting colonization process. Internal structures generated by the construction process and initial substrate characteristics were decisive for distribution and flow of precipitation water as well as for biotic succession. External factors such as episodic thunderstorm events triggered erosion and dissection of the surface during this first phase, promoted by the low vegetation cover and the unconsolidated character of the sandy substrate. Thus, the covering sandy material with very low organic matter content and a loose structure had to be classified as highly erodible. As a consequence, water and sediment were transported and redistributed within the catchment and new structural elements evolved. Immigration of flora and fauna from nearby source habitats was another external process leading to colonization patterns. As a result, an overall differentiation of the catchment area was observed into subareas underlying abrasion or accumulation processes on the one hand and subareas with stable surfaces on the other hand (Schneider et al. 2011). This first phase was short in time and highly dependent on initial structures such as substrate, texture and source habitats of immigrating biota. For the Chicken Creek catchment this phase predominantly in 2007 when the extent of erosion clearly decreased, groundwater tables had reached their preliminary maximum, and the steepest increase of both floristic and faunistic species numbers was already completed. This phase was defined as "geo-phase" as the system was still mainly dominated by substrate characteristics and geomorphic processes (Schaaf et al. 2011). Processes of the second phase were already active here such as dissolution processes triggered by infiltrating water.

Phase II is defined by a growing importance of hydrologic processes, especially the initial groundwater recharge leading to the establishment of a groundwater body in the aquifer. This process depended on infiltration and seepage of precipitation. In addition, seepage through the almost unweathered sediments was further accompanied by the transport of ions from easily soluble salts like gypsum into the groundwater body. The continued colonization by biological soil crusts and vascular plants caused a significant decline of geomorphic processes as the surface became progressively stabilized by these biota. Vegetation established preferentially along the linear structures of former erosion channels, which was probably due to the better growing conditions with respect to water availability of the sediments found here. Also nutrient availability may be improved in these stream beds due to matter relocation and concentration processes. With regard to flora and fauna, species increasingly established in the course of Phase II and the respective populations started to spread within the catchment. Nevertheless, this phase is consistent with the “geo-hydro-phase” of Schaaf et al. (2011): Biota were colonizing but not yet dominating ecosystem performance.

The dissection and stability of surfaces, however, was an important factor not only for the formation of vegetation patterns but also for biological soil crusts. Initially established structures such as soil crusts obviously influenced vegetation patterns by altering soil surface properties and stability as well as by promoting surface runoff and erosion. In the course of Phase II these initial physical and early biological soil crusts were more and more replaced by moss crusts with completely different ecological properties. Mosses are known as an important player in the initial colonization of bare soil surfaces by biological soil crusts and represent late-successional stages of these crusts (Belnap et al. 2001, Spröte et al. 2010). The impact of different types of biological crusts including moss crusts on soil hydraulic properties particularly under temperate humid climate conditions is still unclear and subject to further investigations (Belnap et al. 2001). However, it is assumed that moss crusts have a positive impact on water infiltration and by this may reduce surface runoff. Generally, biological soil crusts influence and induce soil forming processes. Their effect at the micro-scale was described by Fischer at al. (2010, 2012). Later in this phase decalcification as one of the first pedogenic processes became evident as indicated by increasing concentration of inorganic carbon in soil solution and runoff waters.

Finally, Phase III was marked by the gradually growing importance of these soil forming processes as well as of biotic interactions and groundwater discharge. Total cover of vascular plants was growing further and replacing the actual moss crusts step by step. Soil fauna is drastically increasing both in number of species and individuals as well as in the complexity of the soil food web. Hence, both the interactions between flora and fauna as well as the impacts on their abiotic environment will probably gain larger influence. For instance, Boldt et al. (2012) demonstrated the importance of organic carbon and nitrogen inputs into the soil via roots of the legume *Lotus corniculatus*. Particularly, feedbacks between the further development of vegetation and hydrologic properties are expected as a consequence of changing evapotranspiration conditions of the site. By now these interactions between vegetation and hydrology are still less pronounced. Nevertheless, with rising groundwater levels, the main erosion gullies developed to (at least locally) perennial streams and spreading of specific plants such as reed

(*Phragmites australis*) was observed particularly along these erosion rills and at other restricted areas with higher soil moisture. Further, the importance of evapotranspiration as one key factor for lowering the groundwater table in summer when seasonal fluctuations of the groundwater levels were observed is rapidly growing.

Odum (1969) proposed trends of ecological processes to be expected in the development of ecosystems. These trends can be applied to the model of ecosystem development suggested by Fath et al. (2004): The distinct increase in the amount, number, and size of biota in the catchment corresponds to “structural growth”; this holds true for all presented groups, and especially since 2009. Moreover, the increasing complexity of food webs, and the rising importance of higher plants (i.e., macrophytes, trees) reflect slight network and information growth according to Fath et al. (2004), indicating a trend of increasing system organization and efficiency. The transformation of the initial geo-system into areas with evolving terrestrial or aquatic ecosystem characteristics and from a very episodic to a more permanent stream network and discharge, together with the observed biotic dynamics increased site diversity and heterogeneity with respect to water and nutrient availability and transformation processes.

5. Conclusions

Six years of monitoring in the artificial catchment Chicken Creek revealed a highly dynamic development of the initial ecosystem. On the basis of the recorded time series of environmental parameters, three phases of ecosystem development can be distinguished. According to this preliminary classification the system will be governed by biota in the short run.

However, indications of low resilience and stability in different compartments of the system, of below-ground species diversity being still low, and of feedback mechanisms playing a minor role clearly support the assessment that the Chicken Creek catchment is still in a very early, initial state. For the future, it is expected that (i) ecosystem biomass will increase quantitatively in the short term, capturing more of the incoming solar energy, (ii) connectivity both between and within the compartments will further grow, raising the internal organization in the mid-term, and (iii) a delayed qualitative growth to more conservative, energetically efficient patterns will occur. Finally, it is supposed that feedback mechanisms (e.g., primary producers and groundwater development) will intensify with the increasing number of effective structures within the system in the near future. Therefore, investigations of these interactions between different compartments of the Chicken Creek catchment need to be intensified and adapted to the system transitions.

With regard to interdisciplinary ecological research activities this site offers unique opportunities. The multi-temporal observation approach refers to a hierarchy of time scales, ranging from event based, continuous, to periodic measurements, using ground-based (geomorphology, pedology, hydrology, biology, limnology), meteorological and remote sensing techniques. In particular, the gradual growth of heterogeneity and complexity of the ecosystem allows for studies of initial ecosystem development processes and steps. The understanding of this first stage of establishing natural systems based on high resolution time series (Bakker et al. 1996) seems to be crucial for a better understanding of reactions and resilience of ecosystems and feedback mechanisms between different compartments. Furthermore, the highly dynamic development allows for a monitoring of a fast sequence of successional stages and phases within a short period of time. Thus, monitoring techniques designed for the observation of global change reactions on different time scales and on the ecosystem level can be tested, calibrated and validated at sites such as the Chicken Creek catchment with well-known inner structures and previously determined boundary conditions. Therefore, the artificial catchment Chicken Creek initiative contributes very well to other recently established critical zone observation sites amongst Germany and Central Europe.

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Figure captions

Fig. 1: Location of the artificial catchment Chicken Creek in Lusatia, southeastern part of the State of Brandenburg, Germany.

Fig. 2: Map of the artificial catchment (a) and schematic profiles showing inner structures of the site (b).

Fig. 3: Geomorphic development of the Chicken Creek catchment since autumn 2005: Length and area of streambeds in erosion rills in the western and eastern parts of the backslope area as well as the share of the erosion rills that is covered with vegetation, calculated from aerial photographs. Weather data (daily temperature and precipitation values) are given for comparison.

1)no data available in 2010 and 2011: erosion channels were no longer distinguishable from surrounding areas at the aerial photographs due to a dense vegetation cover.

Fig. 4: Development of linear vegetation patterns: Colonization of erosion rills by Coltsfoot *(Tussilago farfara* L.); photograph taken in July 2009.

Fig. 5: Hydrologic development of the Chicken Creek catchment since autumn 2005: Runoff measured in two main gullies (measured west and east of the artificial spring area), average groundwater tables (with range) and changes of pond level and catchment runoff. Weather data (daily temperature and precipitation values) are given for comparison.

1)no data available: measurement started in May 2008

2)no data available: measurement started in July 2009

Fig. 6: Chemical development of the Chicken Creek catchment since autumn 2005: pH values and electrical conductivity in soil solution, runoff and bulk precipitation; sulfate and total inorganic carbon (TIC) concentrations in soil solution, different runoff components and bulk precipitation. Weather data (daily temperature and precipitation values) are given for comparison.

1)no data available: measurements started in July 2006 (weir 1 and 2), May 2008 (flume), and November 2007 (soil solution), respectively

Fig. 7: Biological development of the Chicken Creek catchment since autumn 2005: Cover degree for plants and mosses and plant species number (both from geobotanic monitoring at permanent monitoring plots). Abundance and species number of soil fauna (both from repeated samplings in spring and autumn). Weather data (daily temperature and precipitation values) are given for comparison.

[1] data from only 360 1 m² plots excluding the pond area

[2] conservative estimations on the basis of preliminary determinations

[3] no data available: samples not yet determined

Fig. 8: Faunal profiles representing the food-web condition in relation to its structure (SI) and enrichment (EI) as indicated by the "weighted faunal analysis" (mean ± 1 SE, n = 27); Quadrat A: poorly developed or highly disturbed food web condition, N-enriched, bacterial decomposition channel, low C/N ratio, Quadrat B: maturing food web condition, disturbance low to moderate, N-enriched, balanced decomposition channel, low C/N ratio, Quadrat C: undisturbed, structured food web and relatively low primary production, fungal decomposition channel, moderate to high C/N ratio, Quadrat D: basal or degraded food web condition, depleted, fungal decomposition channel, high C/N ratio.

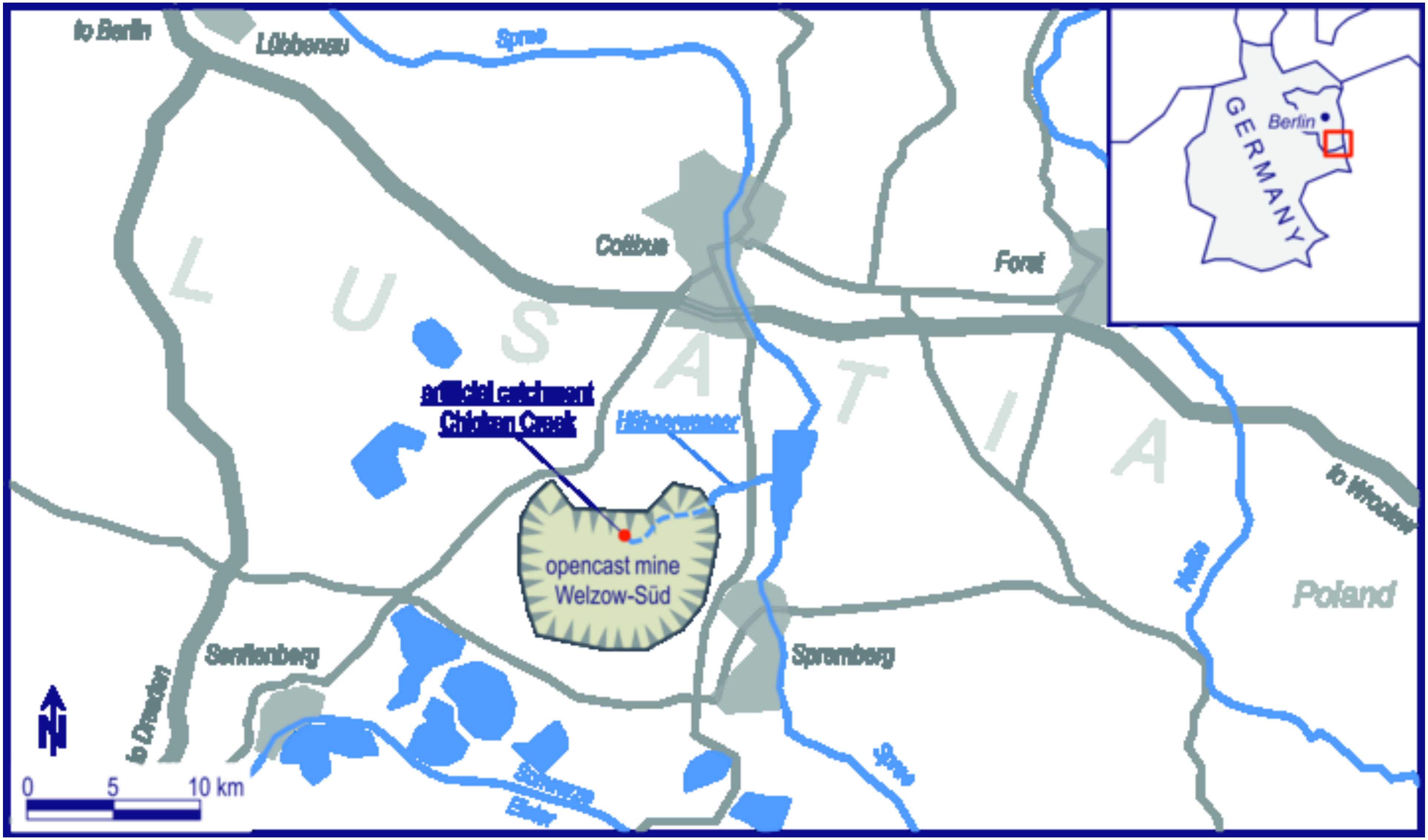
Fig. 9: Schematic overview of intensity (from low to dominating with regard to the qualitative and/or quantitative importance of the respective process at a specific moment) of selected geomorphic, hydrologic, pedogenic and biologic processes and their temporal development during the initial ecosystem stage observed at the Chicken Creek catchment. The indicated phases are characterized in the text.

Tables

Tab. 1: Annual precipitation and average temperature measured at the Chicken Creek catchment compared to long term climate data (normal period 1961-1990, DWD weather station Cottbus, data provided by Deutscher Wetterdienst)

	2006	2007	2008	2009	2010	2011	1961-1990
	Chicken Creek catchment						weather station Cottbus
Temperature [°C]	10.9	11.3	10.9	10.3	9.0	10.9	8.9
Precipitation [mm]	403.4	667.2	659.9	664.9	793.6	639.1	563

Figure 1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Senftenberg
Spremberg
to Dresden
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Figure 2

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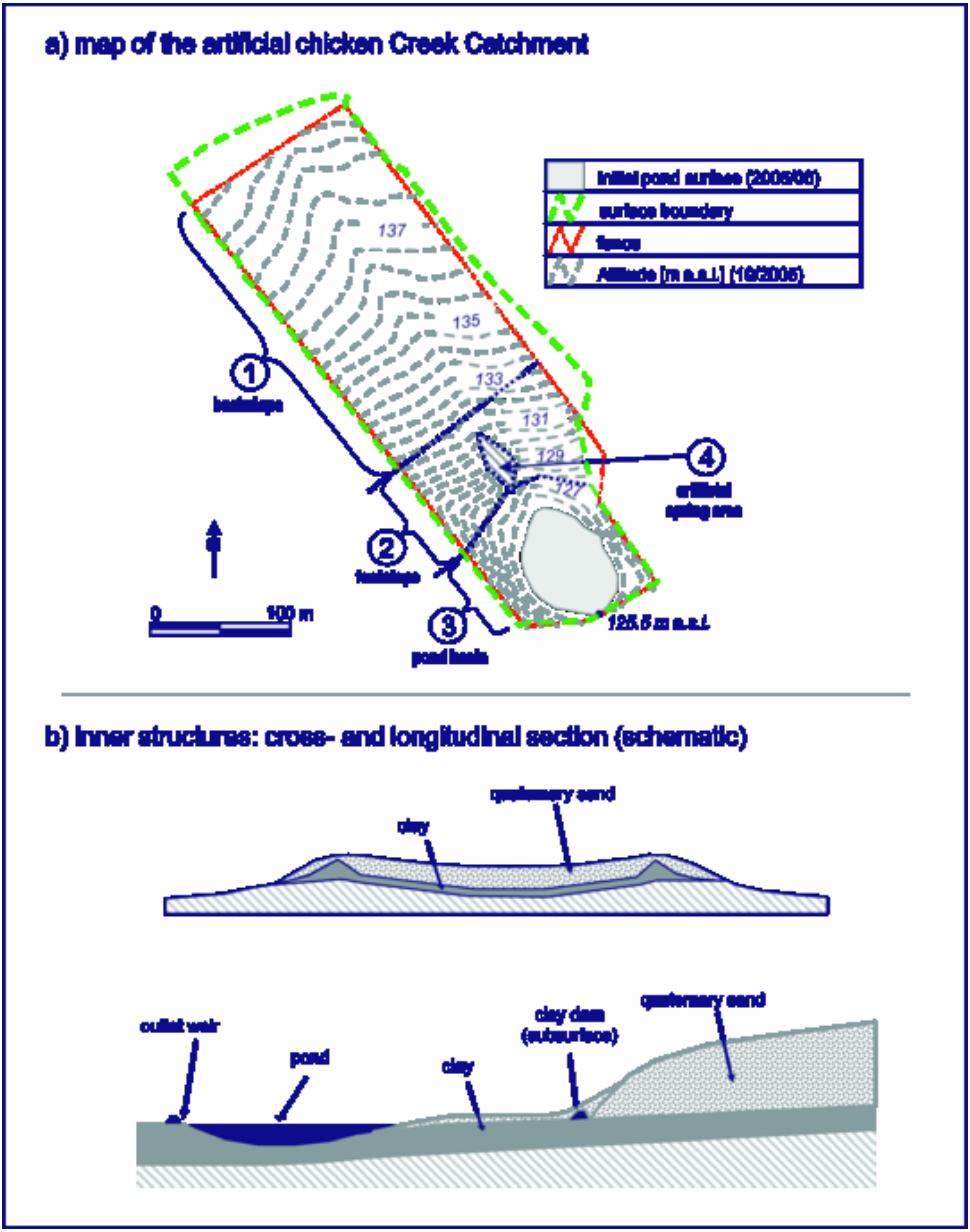

a) map of the artificial chicken Creek Catchment

b) inner structures: cross- and longitudinal section (schematic)

Figure 3

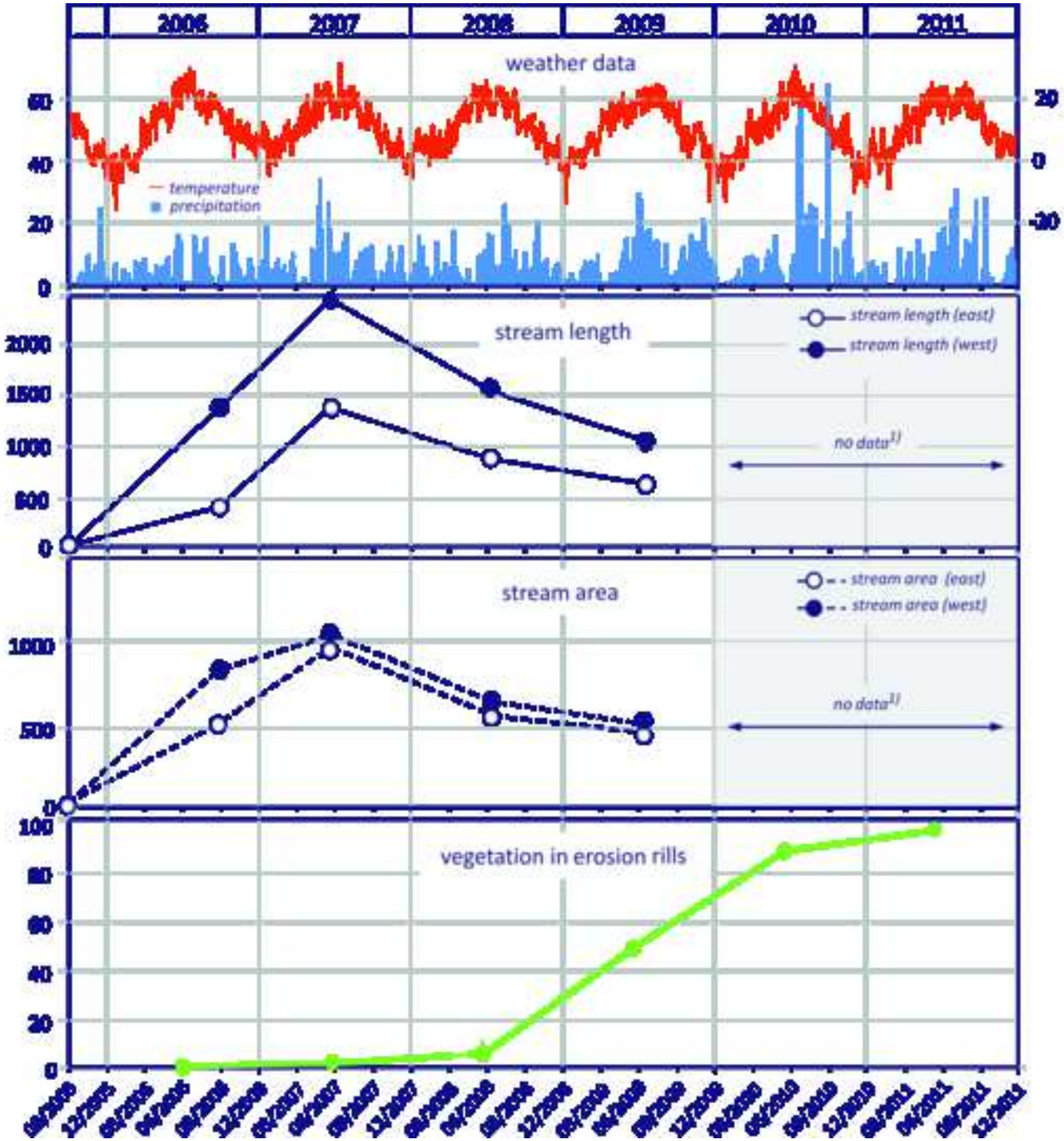
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Figure 4

Figure 5

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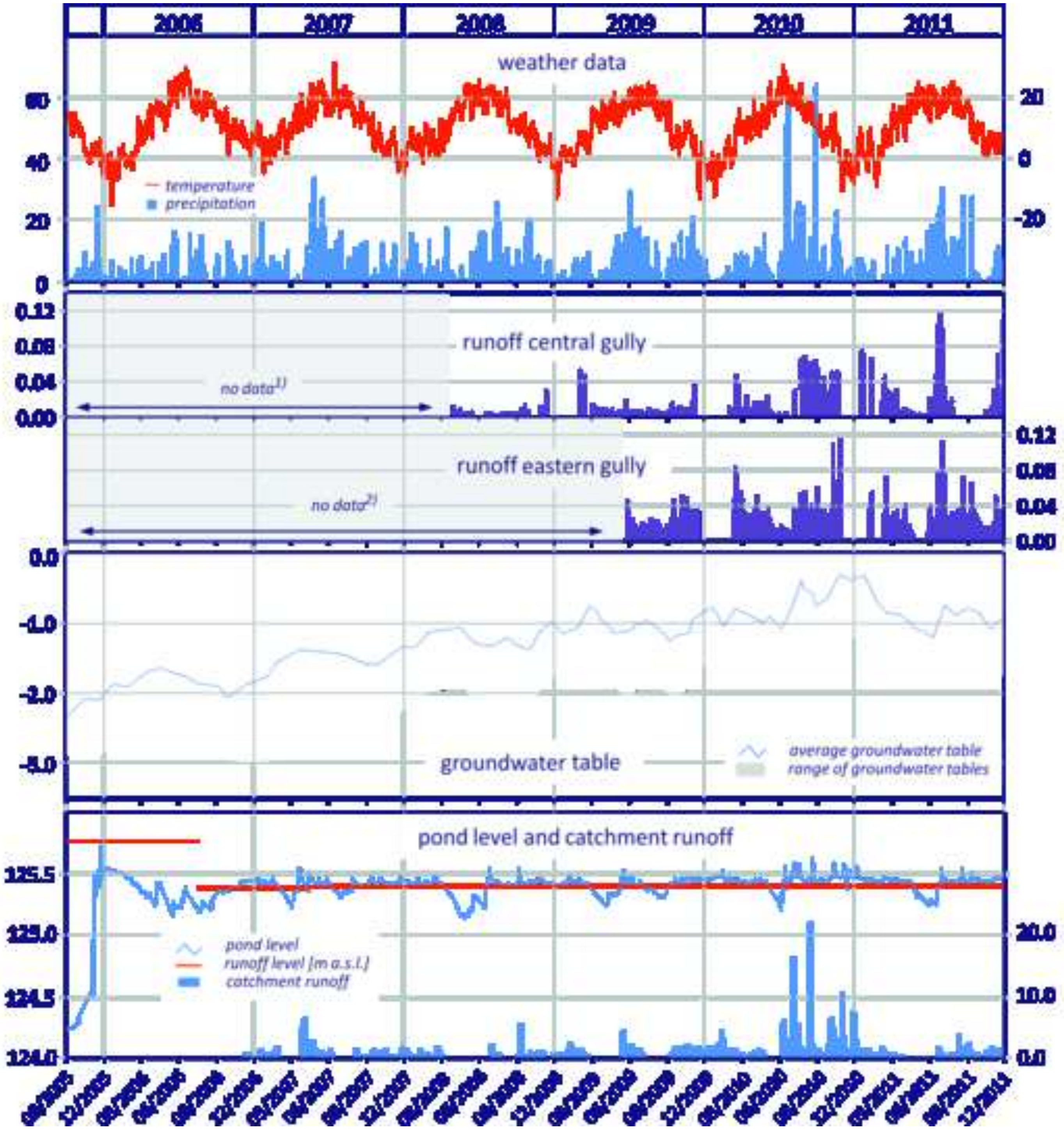

Figure 6

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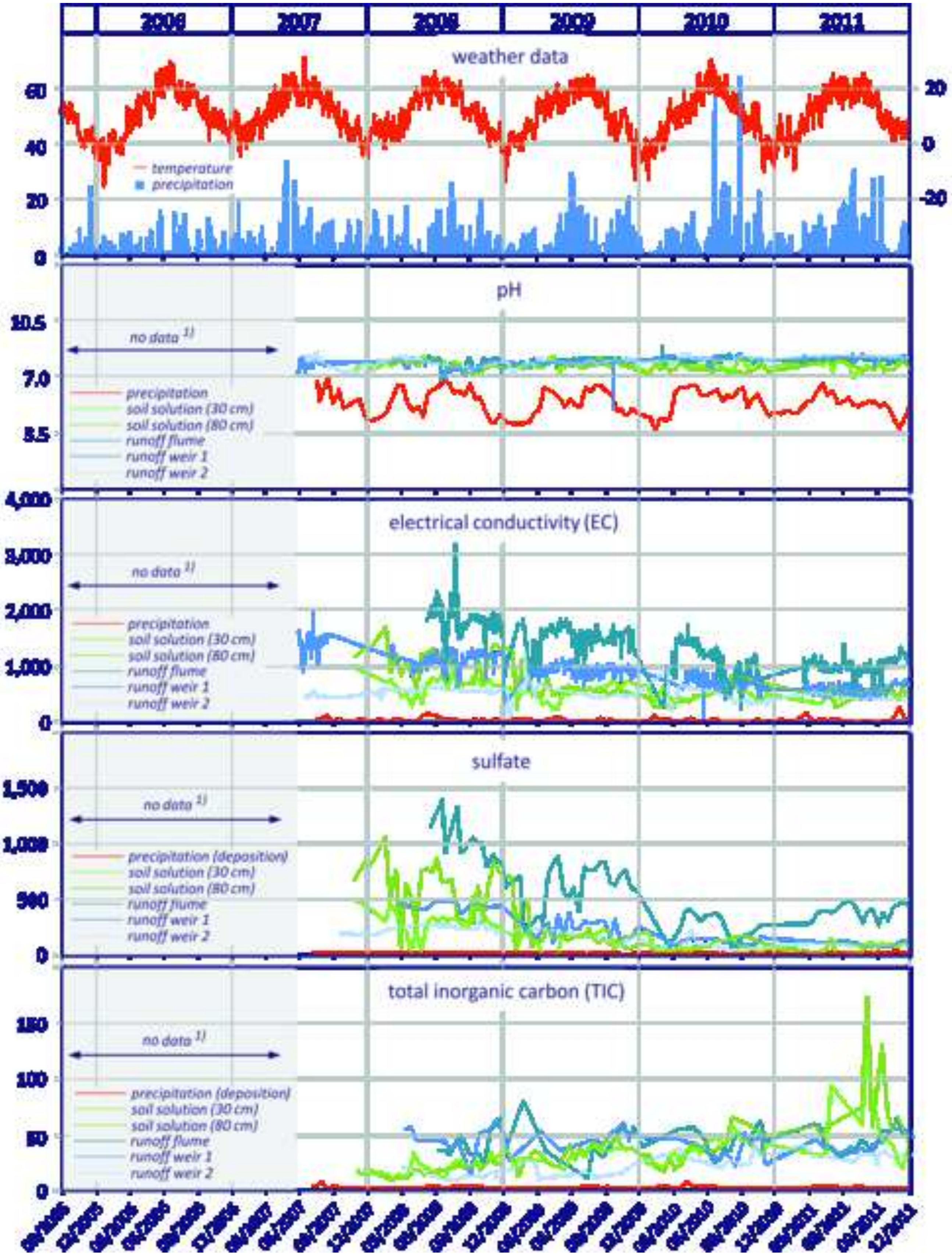

Figure 7

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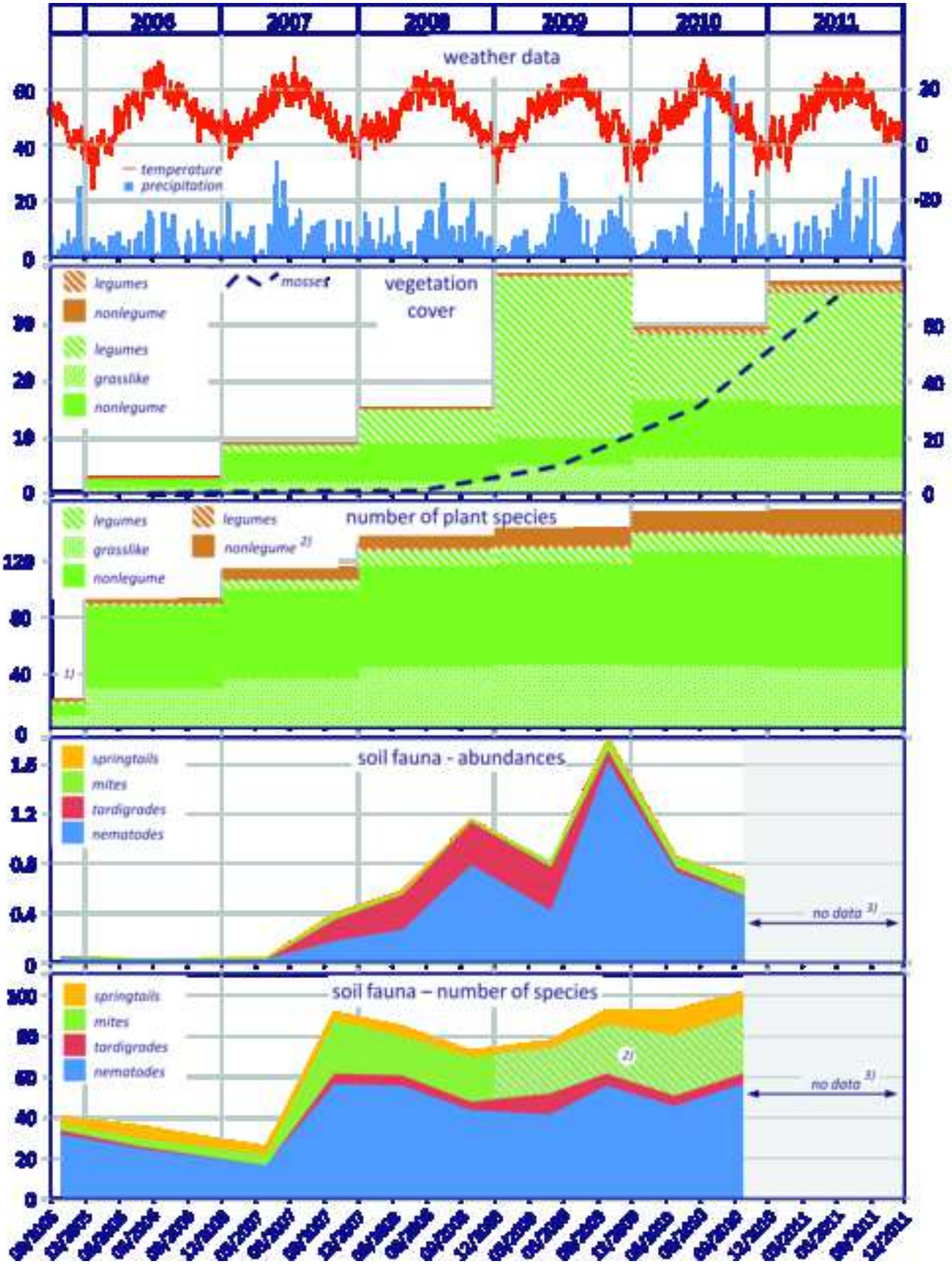

Figure 8

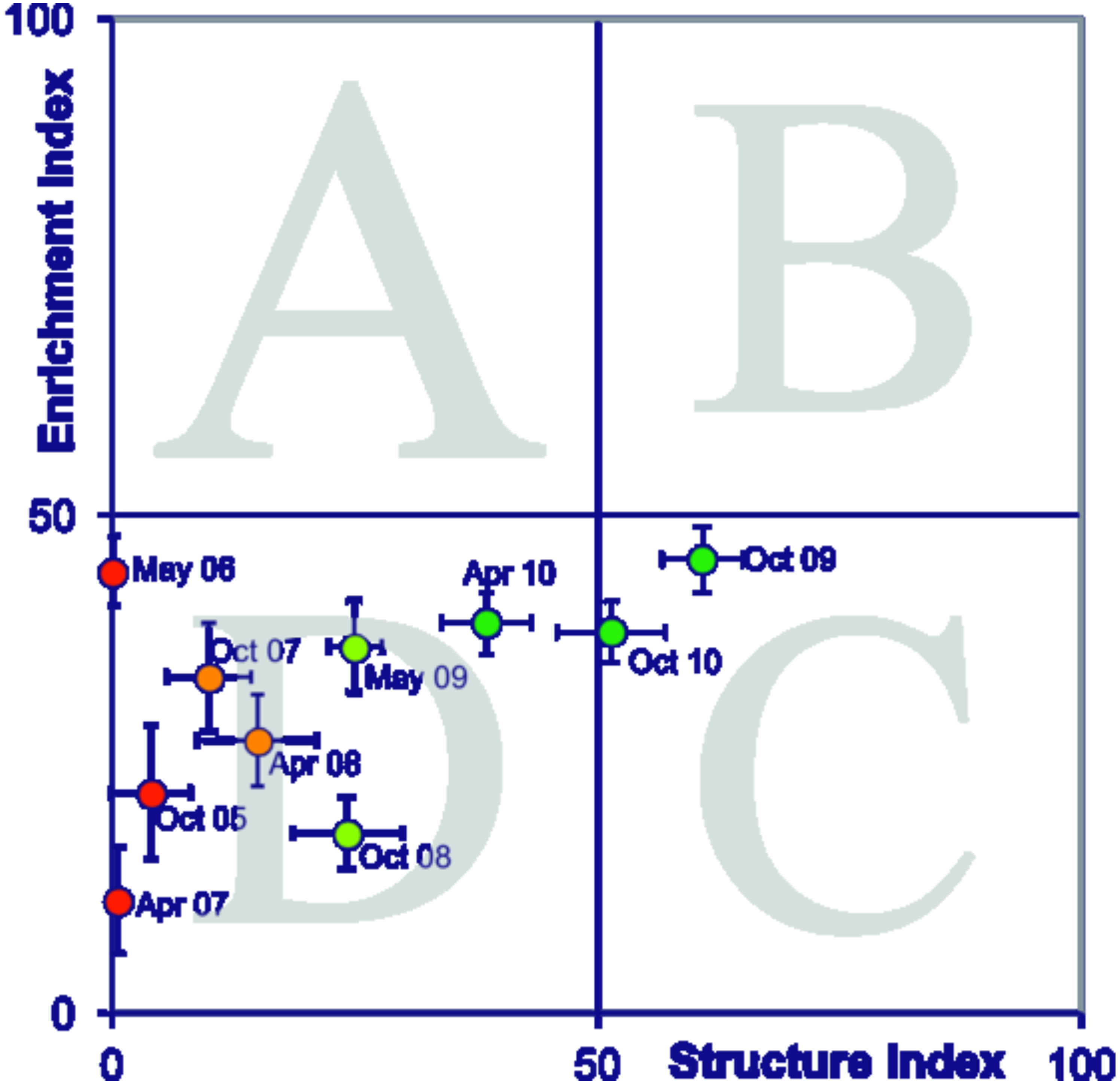
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Figure 9

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