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REVIEW

A holistic approach to groundwater protection and ecosystem services in karst terrains

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Abstract

A holistic conceptual approach to groundwater and natural resources protection, surface and subsurface biodiversity conservation and ecosystem services in karst terrains is presented. Karst landscapes and aquifers consist of carbonate rock in which a part of the fractures has been enlarged by chemical dissolution. They are characterized by unique geomorphological and hydrogeological characteristics, such as rapid infiltration of rainwater, lack of surface waters, and turbulent flow in a network of fractures, conduits and caves. Karst terrains contain valuable but vulnerable resources, such as water, soil and vegetation, and they provide a great variety of habitats to many species, both at the surface and underground, including many rare and endemic species. Karst terrains deliver valuable ecosystem services and act as natural sinks for carbon dioxide (CO_2) thus helping to mitigate climate change. It is demonstrated that all these resources and ecosystem services cannot be considered in an isolated way, but are intensely interconnected. Because of these complex feedback mechanisms, impacts on isolated elements of the karst ecosystem can have unexpected impacts on other elements or even on the entire ecosystem. Therefore, the protection of natural resources, biodiversity and ecosystem services in karst requires a holistic approach.

Keywords Karst ecosystem · Groundwater · Vulnerability · Biodiversity · Soil erosion · Carbon dioxide sink

Introduction

Karst terrains contain many natural resources and provide valuable ecosystem services, such as freshwater for human consumption, aquatic ecosystems and agricultural irrigation, a great biodiversity both at the land surface and in the underground, landscapes and caves with high recreational and cultural value, and soils that provide the basis for agricultural production. Furthermore, the karstification process acts as a natural sink for atmospheric carbon dioxide.

At the same time, all these natural resources and ecosystem services are vulnerable to direct or indirect human impacts. Groundwater resources in karst aquifers are vulnerable to contamination, overexploitation, and climate change (Bakalowicz 2005). Karst landscapes, karst aquifers and caves provide habitats to rare and endemic species that are sometimes restricted to very small areas and thus particularly vulnerable to extinction (Bonacci et al. 2009; Furey et al. 2010; Humphreys 2006; Sket 1999). Soils on karst are extremely vulnerable to irreversible erosion caused by maladjusted agricultural techniques. In turn, agricultural production on karst is vulnerable to soil degradation and

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Preliminary publication information: This paper was already published in 2012 in the (at that time) new journal AQUA mundi that was intended to be included in the Science Citation Index. Instead, the journal collapsed soon afterwards, and all published papers have disappeared without leaving a trace. However, it turned out that concepts and ideas from this paper were often cited. Therefore, several colleagues have encouraged me to republish this paper in a renowned journal. I am grateful to Jim LaMoreaux, Editor-in-Chief of Carbonates and Evaporites, for giving me this opportunity.

This article belongs to a series of "Reviews in Karst Hydrogeology" promoted by the IAH Karst Commission (https://karst.iah.org) with the goal to collect and evaluate current knowledge in different fields of karst hydrogeology and make it available to the scientific community.

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rocky desertification (Feeser and O'Connell 2009; Xu et al. 2011; Yang et al. 2010).

While many studies deal with isolated aspects of groundwater or natural resources in karst terrains, this conceptual paper intends to provide a holistic ecosystem perspective of karst systems, their natural resources and their vulnerabilities—inspired by and as a further development of the earlier publications of Yuan (2001) and Bonacci et al. (2009). The complex interconnections and multiple positive or negative feedbacks in karst ecosystems are also highlighted to demonstrate that the protection of natural resources in karst can only be achieved by a holistic approach that includes sustainable soil cultivation, landscape and biodiversity preservation and groundwater protection.

Only renewable and thus potentially inexhaustible natural resources are considered in this paper, such as water, soil, vegetation and fauna. These resources are vulnerable and require protection and sustainable management. Exhaustible resources, such as hydrocarbons or metal ores, are not considered. Carbonate rock can be used for limestone quarrying, as an exhaustible resource. However, in this paper, it is considered as an integral part of the natural karst environment.

Formation, structure and functioning of karst systems

Karst systems are the result of intense water–rock interactions, most often with strong involvement of the biosphere. Karst landscapes and karst aquifers typically form by chemical dissolution of limestone or other carbonate rocks by water containing carbon dioxide (Dreybrodt 2000):

$$\mathrm{CaCO_3 + H_2O + CO_2 = Ca^{2+} + 2\ HCO_3^-}$$

Most carbonate rock dissolution occurs in the uppermost meters to tens of meters, but calcite dissolution also occurs at greater depth, owing to the non-linear dissolution kinetics of calcite (Dreybrodt 1990; Gabrovsek and Dreybrodt 2001), mixing corrosion (Bögli 1964; Gabrovsek and Dreybrodt 2000) and other processes. These dissolution processes change the hydraulic properties of the rock, as a part of the fractures and bedding planes is enlarged to a hierarchically organised system of interconnected open fractures, conduits and caves.

The highly fractured and intensively karstified uppermost zone of carbonate rock outcrops is called epikarst and often includes biologically active soil material (Williams 2008). The epikarst is characterized by higher porosity and permeability than the rock below. It is often drained by shafts that funnel the water towards a system of conduits and caves. Flow in conduits is frequently fast and turbulent, while lower flow velocities occur in the fractured rock matrix (Kovacs et al. 2005). Many karst aquifer systems drain towards large springs with high variations of discharge, chemical and microbial water quality (Ravbar et al. 2011; Winston and Criss 2004).

Uplift of karst massifs along with erosional deepening of the valleys leads to the drying of caves and the formation of a new active drainage network at greater depth (White 2007). Dry caves can transform into stalactite–stalagmite caves and provide habitats for bats and other terrestrial organisms, while water-filled conduits are habitats for aquatic species (Christman and Culver 2001).

As a consequence of the highly permeable karst drainage system, there is no surface runoff in many karst areas, even under extremely humid climatic conditions. In many case, all effective precipitation (minus evapotranspiration) infiltrates underground through permeable soils and epikarst (autogenic recharge). Streams from adjacent non-karst areas often sink underground via swallow holes near the contact to karst rock (allogeneic recharge). Sinking streams and large karst springs illustrate the intense groundwater–surface water interaction in karst terrains (Fig. 1).

Soils on karst often consist of three main components: limestone blocks, organic matter and residual non-soluble minerals, such as clay or silt. Soils in lowland karst areas that have experienced long periods of continental weathering often consist of thick residual sediments, while soils in upland karst are thin and patchy. In some cases, the soil only fills fissures and pockets in the epikarst, which leads to a patchy distribution of vegetation and soil fauna (Bautista et al. 2011; Jiang et al. 2008).

Interconnected resources and ecosystem services

Freshwater

According to UNESCO "Groundwater contained in aquifer systems represents the most significant as well as the safest source of drinking water" (Aureli 2010). Ford and Williams (1989) have estimated that karst aquifers supply drinking water for about 25% of the global population. Although this is probably an overestimation, this number illustrated the importance of karst aquifers as freshwater resources. In some countries, such as Austria or Slovenia, karst water contributes about 50% to water supply (Ravbar and Goldscheider 2007). The city of Vienna with its 2 million inhabitants is entirely supplied by karst water (Maloszewski et al. 2002). Many regions and cities in Italy are also supplied by karst waters, including the capital with its 2.8 million inhabitants in the city area. Since pre-Christian time and even today, Rome is predominantly supplied by water from several large karst springs (Kresic and Stevanovic 2010). The South Italian

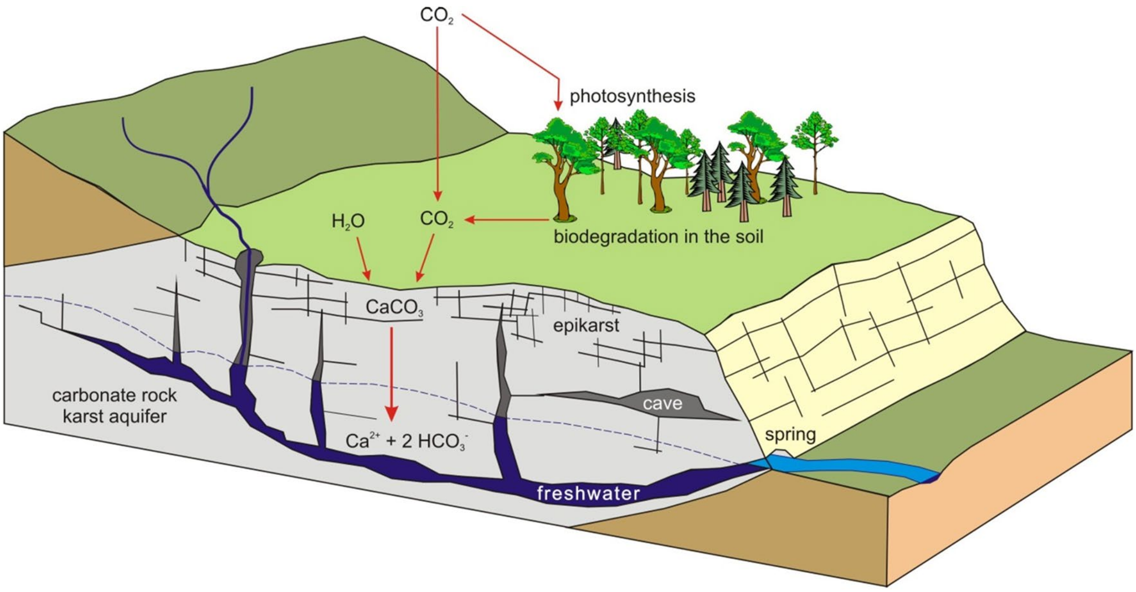

Fig. 1 Schematic illustration of a karst system, its natural resources and relevant processes (modified after Goldscheider and Drew 2007)

Campania Region with several million inhabitants also heavily depends on karst water sources (De Vita et al. 2012; Fiorillo and Doglioni 2010). The Edwards Aquifer in Texas, USA, is another important example of a karst groundwater resource supplying millions of people, including several big cities, such as San Antonio (Chen et al. 2001; Wong et al. 2012). China is the country where the largest number of people rely on karst water resources, probably more than a hundred million (Lu et al. 2006).

At the same time, karst aquifers are particularly vulnerable to contamination, because of their hydrogeological structure: contaminants can easily enter the aquifer through thin soils and the epikarst or via swallow holes. In the aquifer, they can rapidly spread over large distances in the conduit network and impact springs or wells used for water supply (Goldscheider 2005).

Despite this often-emphasized vulnerability, some karst aquifers deliver drinking water of excellent quality. This can be attributed to favourable hydrogeological settings, such as thick overlying layers (protective cover), absence of sinking streams and swallow holes, thick unsaturated zone, large reservoir with deep regional flow systems. However, in many cases, clean groundwater can be found in healthy karst ecosystem with undisturbed soils and vegetation that provide valuable ecosystem services in natural water purification. In turn, clean groundwater emerging from karst springs provides the basis for health aquatic ecosystems (Bonacci et al. 2009).

Soils

Soils on karst are the basis for natural vegetation and soil fauna, but also for agricultural land use including livestock holding. It is generally difficult to define the thickness of soil on karst limestone, because the soil tends to fill pockets, grikes (karren) and open fissures in the limestone.

The typical soil type on karst is rendzina, characterized by an A–C profile. The A horizon is the organic-rich and biological active layer, while C consists of limestone, partly loosened by weathering (Blume et al. 2002). Owing to the mechanical and geochemical contrast between the soft A and the hard C horizon, rendzina soils are particularly vulnerable to soil erosion (Fig. 2). Mechanical action by cattle, agricultural machines or other activities can easily damage the A horizon and leave nothing, but naked limestone. Similarly, removal or degradation of the vegetation can cause rapid soil erosion by intense precipitation (Feeser and O'Connell 2009; Kheir et al. 2008; Yang et al. 2010).

The mineral phase of soils on karst generally originates from carbonate rock dissolution, although aeolian sediments (loess) can additionally contribute to soil formation (Kufmann 2003). In karst regions adjacent to volcanic areas, such as Southern Italy, pyroclastic deposits can also substantially contribute to soil formation and influence epikarst development (Celico et al. 2010).

Limestone often contains 1–10% non-soluble minerals (Dreybrodt and Kaufmann 2007; Ford and Williams 2007).

Fig. 2 Soil erosion and "rocky desertification" in a Chinese karst landscape. Soils on karst are particularly vulnerable to erosion and the loss of soil is largely irreversible on a human time scale

The rate of limestone dissolution depends on precipitation and other hydro-climatic and biogeochemical factors. In many cases, limestone dissolution is in the range of 10–100 mm in 1000 years (Gabrovsek 2007; Groves and Meiman 2005; Sweet et al. 1976). This means that limestone dissolution typically generates 0.1–10 mm of residual minerals in 1000 years. These numbers illustrate that soil erosion on karst is irreversible on a human time scale.

Biodiversity

Biodiversity in karst areas can be subdivided into surface and subsurface biodiversity. Biodiversity at the land surface of karst terrains is not fundamentally different to biodiversity of non-karst areas. Sunlight is the energy source for the primary production of organic material by plants. Dead plant material is partially degraded in the soil, by the action of soil fauna, fungi, and microorganisms. Plants are also the basis of the food web for herbivore and, eventually, carnivore animal species.

Underground karst ecosystems are characterized by the absence of sunlight. There is no primary production of organic matter by plants or algae, but the food web is entirely based on imported organic matter from the land surface (Hancock et al. 2005). Therefore, subterranean biocenoses consist of animals, fungi, and microorganisms (Humphreys 2006). Specific cave biocenoses that use geochemical energy sources, such as sulphide oxidation, are not discussed here (Engel 2007).

Subterranean live can best be observed in caves, but also exists in smaller cavities and fissures. Subterranean species can be grouped into terrestrial and aquatic. The terms used to describe these species are trogloxenes/stygoxenes, troglophiles/stygophiles and troglobites/stygobites (Culver et al. 2000). The prefix troglo refers to (air-filled) caves whereas stygo stands for groundwater. Trogloxenes (cave visitors) are species that frequently visit caves (e.g., for shelter), but must leave the cave to complete their live cycles. Bats are prime examples of trogloxenes. Troglo- and stygophiles live in caves or groundwater and can complete their life cycles there, but can also live in suitable surface habitats. Troglobites and stygobites are species that only live underground, in caves or groundwater, and are totally adapted to a life without sunlight. These species usually have no eyes and no skin pigments. Blind caves fish and cave salamanders (e.g., *Proteus anguinus*) are prime examples of this group (Felice et al. 2008; Pezdirc et al. 2011; Voituron et al. 2011).

Subterranean life can also be found in other geological environments, such as alluvial aquifers, but the corresponding biocenoses mostly consist of very small invertebrates (Danielopol and Pospisil 2001). Karst aquifers offer a greater diversity of subterranean habitats and larger voids than other subterranean environments. Therefore, the troglo- and stygofauna of karst includes a greater biodiversity and also larger species (Christman and Culver 2001; Elliott 2007).

Subterranean biocenoses are often characterized by a high number of rare and endemic species (Achurra and Rodriguez 2008), because of their high degree of isolation. Troglo- and stygobites cannot leave their underground habitats and are thus often restricted to one single karst or cave system. Many underground species are still undiscovered, and surveys of underground biodiversity at a previously unexplored karst location often reveal new species (Clements et al. 2006). Therefore, destruction or contamination of karst habitats is likely to lead to the extinction of unknown species. The epikarst also provides habitats for specifically adapted biocenoses (Pipan et al. 2008).

Some of this also applies to karst ecosystems at the land surface: Although less isolated than caves, they are often quite different to adjacent landscapes in terms of topography, geomorphology, hydrology, soils, and vegetation (Aukema et al. 2007; Moran et al. 2008). Karst landscapes offer a great variety of different habitats than non-karst landscapes and are often relatively isolated from their surroundings. Therefore, they host a great biodiversity of animal and plant species, including rare and endemic species (Clements et al. 2006). For example, Delacour's langur (*Trachypithecus delacouri*), one of the most endangered primate species, is endemic to some Vietnamese karst areas (Tuyet 2001; Workman 2010) (Fig. 3). This primate is the highest species endemic to karst.

Karst as carbon dioxide sink

The aforementioned hydrogeochemical equation illustrates the role of karst processes as a carbon dioxide sink. In karst terrains without soil and vegetation (e.g., alpine or arctic areas) CO_2 only comes from the atmosphere. CO_2 partial pressures in the atmosphere have steadily increased from 316 ppm in 1959 to 392 ppm in 2011 (Manua Loa Observatory 2012). For a given CO_2 partial pressure in the air, the equilibrium concentration in water only depends on temperature: The lower the temperature, the higher the CO_2 concentration in water (Dreybrodt 2000).

When soils and vegetation are present, the larger part of the CO_2 comes from the biodegradation of organic matter in the soil. In this case, the photosynthesis of plants is the primary process that removes CO_2 from the atmosphere and transforms it into living organic material, while microbial degradation of dead plant material generates CO_2 at highly variable levels, depending on many factors, such as soil structure, type and content of organic matter, and temperature. Soil CO_2 partial pressures range between atmospheric levels (0.039%) and 10% with 0.5–5% as the typical range, i.e., about 10–100 times higher than in the atmosphere (Liu et al. 2007). A part of this CO_2 is dissolved in soil water and enters the deeper underground, where it reacts with carbonate rock to form dissolved calcium cations and bicarbonate (HCO_3^-) anions in the groundwater.

Consequently, karst systems covered with soil and vegetation are more efficient as CO_2 sinks than bare carbonate rock outcrops, for three main reasons: (1) photosynthetic CO_2 uptake by the vegetation; (2) carbon storage in organic-rich rendzina soils; (3) increased microbial CO_2 production in the soil and subsequent neutralization by carbonate rock dissolution (Liu et al. 2010).

Liu et al. (2008) have estimated that karst processes account for 10% of the total anthropogenic CO_2 emission, or 29% of the "missing CO_2 sink". Recent studies suggest that the role of carbonate rock weathering as a CO_2 sink had previously been underestimated by a factor of 3, while the role of silicate weathering has been overestimated (Liu et al. 2011).

Recreational and cultural value of karst landscapes and caves

Karst landscapes and caves have high recreational, cultural and historical values. Many artefacts documenting early human development have been preserved in karst and cave settings, such as bones and fireplaces of early men, cave

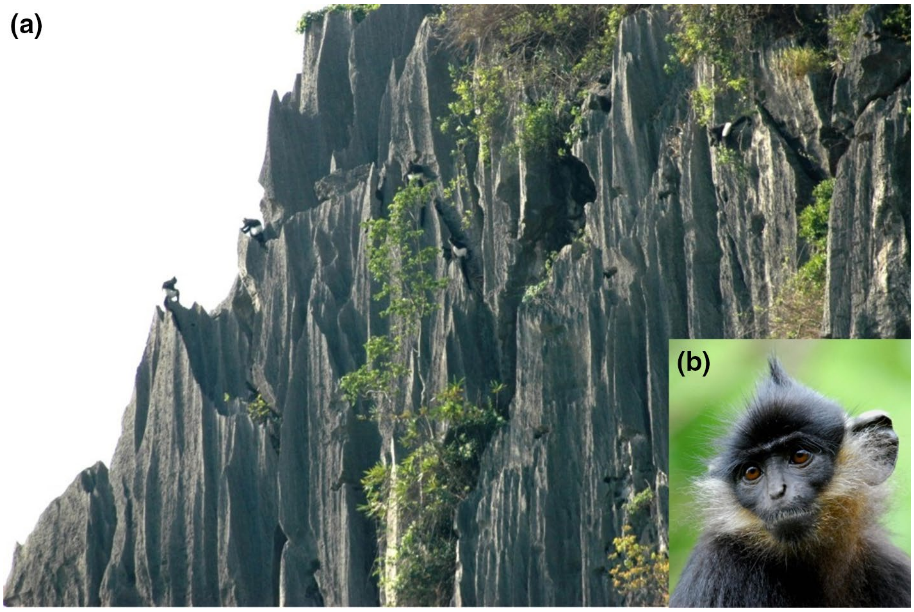

Fig. 3 Delacour's langur, one of the most endangered primate species, is endemic to some Vietnamese karst regions: **a** several specimen in their natural karst habitat, **b** an individual langur in the Endangered Primates Rescue Centre (EPRC) in Vietnam (photos: Tilo Nadler, EPRC)

paintings, early piece of artwork, and the first music instrument, a 35,000 years old flute found in a cave in Germany (Münzel et al. 2002).

In 2007, approximately 50 karst sites were on the list of UNESCO world heritage site, for various reasons, such as landscape, cultural value or biodiversity (Hamilton-Smith 2007). Re-evaluation of the current list revealed that 41 site descriptions refer to caves, 12 site descriptions mention karst as the major cultural or natural value, and 16 descriptions name limestone or dolomite as the characteristic rock type. The most prominent UNESCO karst and cave world heritage sites include South China Karst, Ha Long Bay in Vietnam, the Škocjan Caves in Slovenia, the Mammoth Cave and Carlsbad Caverns, which are at the same time US National Parks, and the Plitvice Lakes National Park in Croatia. The latter is a prime example of a groundwater-dependent aquatic ecosystem supplied by water from a regional karst aquifer system (Biondic et al. 2010). These few examples illustrate the natural, cultural, touristic and recreational value of karst landscapes and caves all over the world.

Synthesis: karst ecosystem resources and services

This paragraph and Fig. 4 summarize how the natural resources and ecosystem services described in the previous sections are connected in a healthy karst ecosystem.

Carbonate rock provides the geological and geochemical basis of any karst ecosystem. Soils on karst result from biological activities and mainly consist of organic matter and residual minerals from carbonate dissolution. Soils are the basis for both natural vegetation and agricultural production on karst. Karst area covered with soil and vegetation are more efficient as a natural CO_2 sink than bare limestone outcrops. Soils also contribute in many ways to the natural protection of groundwater against contamination. For example, clay minerals in soils adsorb heavy metals, while microbial activity in the soil can cause biodegradation of organic contaminants (Shepard and Gutierrez 1999).

Water is probably the most important natural resource in karst, for man and ecosystem. At the same time, water connects all processes, natural resources and ecosystem services in karst: karst aquifers, karst landscapes and caves are the results of water–rock interaction. The availability of water determines the efficiency of karst processes as a CO_2 sink (Liu et al. 2008). Water is the main agent of soil formation and soil erosion. Many karst areas are hotspots of biodiversity (Danielopol et al. 2002), because karst offers a variety of habitats, at the land surface, in the epikarst and in the underground, in water-filled and air-filled fractures and caves. Surface and subsurface biodiversity rely on clean water. In turn, healthy vegetation and biocenoses contribute to the natural purification of water in karst areas, as in other hydrogeological environments (Postel and Thompson 2005).

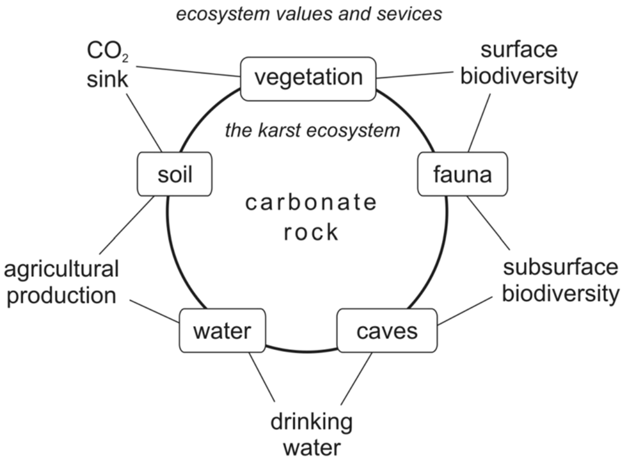

Fig. 4 Generalised presentation of an undisturbed karst ecosystem and its natural resources that represent a variety of values and provide ecosystem services

Interconnected vulnerabilities and impact pathways

Because of the high degree of interconnectivity of karst ecosystems, direct impacts on a single element of the karst ecosystem can have serious indirect consequences for other elements or the entire karst ecosystem (Fig. 5). For example, karst areas are particularly vulnerable to soil erosion so that maladjusted land-use practices can lead to a rapid and irreversible loss of soil and to "rocky desertification"—a major environmental problem in China (Fig. 2) (Kheir et al. 2008; Xu et al. 2011). Soil erosion can lead to declining food production in agricultural areas. Degradation of natural vegetation and soil erosion often depend on each other, i.e., vegetation degradation can cause erosion and vice versa (Feeser and O'Connell 2009).

Soil erosion and the associated decline of vegetation and biological activity also reduce the efficiency of karst

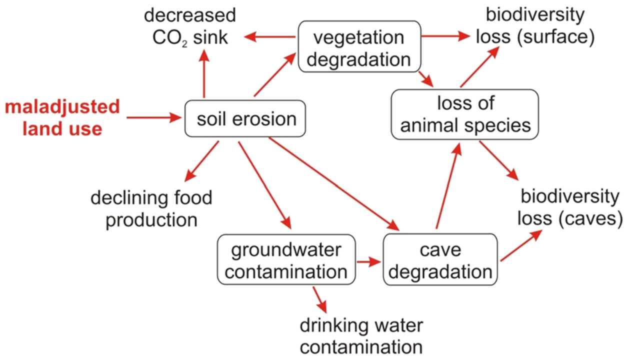

Fig. 5 Exemplified illustration of interconnected vulnerabilities and impact pathways damaging a karst ecosystem and reducing its natural values and ecosystem services

landscapes to act as a natural sink for atmospheric CO_2 (Liu et al. 2010). However, other studies, from non-karst areas, report that soil erosion acts as a net sink for CO_2, because it transports organic particles to the sea where they are trapped in sediments (Dymond 2010).

Soil erosion impairs groundwater quality, for two main reasons: (1) suspended soil particles act as transport vectors for contaminants (Mahler et al. 1999, 2000; Pronk et al. 2009); (2) the soil is an important part of the natural protective cover—a loss of soil consequently means increased groundwater vulnerability (Ravbar and Goldscheider 2007). Deterioration of groundwater quality will also impact aquatic biocenoses in the aquifer and in associated surface waters.

Soil erosion and vegetation degradation also result in a loss of habitats and thus a decline in biodiversity at the land surface (Pimentel and Kounang 1998; Stoate et al. 2001; Zaimes et al. 2012). Direct and indirect impacts of soil erosion and increased sediment transport on subsurface biodiversity are hypothesized but have not yet been studied in detail.

Conclusion

Karst systems contain many natural resources, host a high biodiversity and deliver valuable ecosystem services. All these resources and services are particularly vulnerable to human impacts and interconnected in complex ways that are still incompletely understood. Impacts on isolated elements of the karst ecosystem can have unexpected impacts on other elements of the karst ecosystem. For example, groundwater contamination can lead to the extinction of endemic and yet undiscovered species in the karst aquifer and thus to a loss of biodiversity. Soil erosion can also cause groundwater contamination and decrease the effectiveness of the karst system to act as a natural sink for carbon dioxide. Therefore, the protection of karst groundwater, biodiversity, natural resources, and ecosystem services in karst terrains requires a holistic approach:

- Integrated vulnerability and risk mapping at regional to international scales as a basis for the prioritisation of protection measures. At least the most valuable and vulnerable zones should be protected. This approach includes groundwater vulnerability mapping, but should be extended to biodiversity, soils and other karst ecosystem values and services.
- Adapted land-use practices to avoid soil erosion, vegetation degradation and groundwater contamination. This includes the selection and cultivation of adequate plant species, low-intensity soil cultivation (e.g., non-plough tillage), the avoidance or at least reduced and temporally adapted, intelligent use of agrochemicals and fertilisers (taking into account the hydrologic variability of karst), and the preservation or construction of terraces.
- Highest protection status for the most valuable karst areas. Many more karst regions worldwide have the potential to be included on the UNESCO world heritage list, to be designated National Park or to receive another type of high protection status, based on their biodiversity, freshwater resources, unique geomorphology or valuable caves.

This latter measure will also help to increase the public awareness of karst, which is another crucial point: the public and the politicians need to be informed about the value and vulnerability of karst.

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