

Alnus viridis expansion contributes to excess reactive nitrogen release, reduces biodiversity and constrains forest succession in the Alps

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Abstract Reduction in land use and complete land abandonment are widespread in mountainous regions and are mainly driven by socio-economic factors. Following land-use decline, shrubs and trees expand rapidly into montane and subalpine grassland and alter ecosystem properties at a large scale. In particular, the N₂-fixing shrub *Alnus viridis* is currently spreading at a breath-taking speed and thereby reduces biodiversity, leads to substantial reactive nitrogen enrichment and suppresses species succession towards coniferous forests across large areas in the Alps. In addition, this shrub vegetation neither protects against avalanches nor does it secure slopes from erosion. The expanding, monotonous *A. viridis* shrubland is impenetrable for hikers and diminishes scenic beauty and touristic value of the landscape. Actions and management adaptations are needed to halt the expansion of *A. viridis*. Goats and the traditional sheep breed Engadine sheep proved to be very effective in preventing and reverting shrub expansion because of their specific browsing behaviour.

Keywords Alder · Alps · Browsing · Land use · Nitrogen fixation · Shrub encroachment

Introduction

Around 5,000 years ago, settlers started to clear forests in the Alps, which led to a mosaic of pastures and meadows (Bätzing 2005). Over millennia, this rangeland has been

grazed by domestic and wild animals, used for haymaking and hence, served for fodder and food production. Human activity has been shaping the landscape, and the type of land use has been affecting the distribution and composition of plant communities (Lueth et al. 2011; Tasser and Tappeiner 2002). Modernisation of agriculture has mostly been driven by socio-economic factors and started in mountainous regions during the mid-twentieth century (Rey Benayas et al. 2007). It has fundamentally changed agriculture: on one hand, there has been—and still is—intensification on productive and easily accessible agricultural land (Fischer et al. 2008; Tasser and Tappeiner 2002). On the other hand, poorly accessible or low-productive land has been less intensively used or has been completely abandoned, i.e. meadows have been converted to pastures and former pastures have often been given up. Overall, land abandonment is the dominant process of land-use change in the Alps and between 1985 and 2009, 42.5 % of montane farms disappeared in Switzerland (Federal Statistical Office of Switzerland 2013). The area of montane and alpine pastures decreased drastically, whereas the forest area increased by at least 40 % in Switzerland during the past 150 years (percentage values are here calculated without shrubland; Brändli 2010).

This massive land-use change has substantial implications for ecosystem functioning. Ecosystem properties that have developed over centuries of human influence are being altered within a few decades only, with the expansion of forests and shrubland exerting the most significant change. Beside shrubland and forests, dwarf shrubs of the genus *Calluna*, *Vaccinium* and *Rhododendron* are rapidly expanding into montane and alpine grassland and often form dense carpets (Bischof 1984; Tasser and Tappeiner 2002).

From 1993/95 to 2004/06, shrubs have overgrown an area of around 11,700 ha in the Swiss Alps (Brändli 2010). In Switzerland, *Alnus viridis* [Chaix] DC (green alder)

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contributes 71 % to the shrubland and has overgrown an area of 46,000 ha by 2004/06. Similar expansions of *A. viridis* were observed in the French Alps, for example in the Vanoise National Park, where 7 % of the montane and subalpine area was covered by *A. viridis* shrubland in the late 90s (Richard 1989). Not only the Alps are affected by expanding *Alnus* shrubs: *Alnus viridis* ssp. *fruticosa* has been reported to expand in Alaska and Canada (Myers-Smith et al. 2011) and in Siberia (Frost and Epstein 2014).

Alnus viridis is an early successional shrub that occurs naturally in disturbed habitats such as avalanche tracks, moist ravines or edges of small, steep creeks (Bischof 1984). This species belongs to the native flora of the Alps (David 2010) and has a wide elevational range from about 900 m a.s.l. to the treeline (>2,000 m a.s.l.; Richard 1967). *Alnus viridis* lives in symbiosis with the actinomycete *Frankia alni*, forming typical root nodules within these, protected from oxygen, N_2 is transformed into ammonia by means of the nitrogenase enzyme complex (Dawson 2008). For *Alnus viridis* ssp. *sinuata* and *Alnus viridis* ssp. *crispa*, nitrogen fixation rates of 20 up to 62 kg N ha⁻¹ a⁻¹ have been reported (Binkley 1981). These subspecies are native to North America, have similar stature and habitat preferences as *Alnus viridis* [Chaix] DC. Ongoing research in the Swiss Alps revealed that the N input of *A. viridis* is of a similar magnitude as of the N-American relatives (Bühlmann et al., unpubl.; Hiltbrunner et al. 2014) and thus, by far exceeds the critical load of nitrogen for these former mountain grasslands (Bobbink et al. 2011). The nitrogen fixation rates are considerably larger than the current total input by atmospheric nitrogen deposition, which is in the range of 5–10 kg N ha⁻¹ a⁻¹ for the alpine and 10–15 kg N ha⁻¹ a⁻¹ for the montane belt in Switzerland (Hiltbrunner et al. 2005; modelled data provided by Meteotest, Switzerland). Owing to its ability to symbiotically fix nitrogen, *A. viridis* grows more rapidly than most other woody species: its rate of spreading is two to three times faster than the current forest expansion in Switzerland (calculated from data of Brändli 2010). The sudden release of open terrain by reducing centuries-old land care in the immediate vicinity of natural *A. viridis* habitats contributes to the extraordinary spreading of this species across the Alps.

Changes in ecosystem properties

Biodiversity

Montane and alpine grassland ecosystems are hotspots for plant species diversity (Fischer et al. 2008) and are richer in plant and animal species compared to montane shrubland or forests (Koch et al. 2013; Zoller et al. 1984). Either intensification or abandonment causes the montane land cover to

become more uniform and, thus, reduces plant species richness at different spatial scales (Fischer et al. 2008; Niedrist et al. 2009; Spehn et al. 2006). This loss in biodiversity is amplified by the excessive nitrogen input via the *Alnus*–*Frankia* symbiosis: increased nitrogen availability leads to a decline in plant species richness because nitrophilic, fast-growing species outcompete slow-growing species (Suding et al. 2005). As *A. viridis* shrubs expand, only a few plant species can cope with the shady, cool and moist conditions beneath the *Alnus* canopy, forming a rather species-poor, dense understory vegetation with species such as *Adenostyles alliariae*, *Cicerbita alpina*, *Rumex alpestris*, *Achillea macrophylla* and *Thalictrum aquilegifolium*. The intermediate mosaic stage of grassland mixed with a few *A. viridis* shrubs is often temporarily favourable for plant species richness, but as soon as the *A. viridis* cover exceeds 50 % of the total cover, plant species richness drops to less than half of the former plant diversity in grassland (Anthelme et al. 2001; Bischof 1984). As a consequence of the loss in plant species diversity, the arthropod diversity declines as well (including butterflies; Anthelme et al. 2001; Zoller et al. 1984). In addition, dense *A. viridis* shrubland is not suitable for nesting for the endangered species *Tetrao tetrix* (black goose) and does not provide enough arthropods for their chicks during summer.

Soil, water and climate

Nitrate leaching to streamlets and groundwater generally occurs as soon as soils become nitrogen saturated (Aber et al. 1989). Soils are saturated when their storage capacity for nitrogen is exceeded and the availability of nitrogen compounds exceeds the total combined plant and microbial nutritional demand. For *A. rubra*, which is, in contrast to *A. viridis*, a tall tree, nitrogen leaching rates (in form of nitrate) of up to 50 kg N ha⁻¹ a⁻¹ were reported (Binkley et al. 1992; Compton et al. 2003). Measurements with suction cups in soils under *Alnus viridis* in central Switzerland revealed very high concentrations of nitrate in soil water below the main rooting horizon, frequently exceeding the Swiss threshold for freshwater (25 mg NO₃⁻ L⁻¹), whereas the soil solution in adjacent pastures was nearly free of nitrate (Bühlmann et al., unpubl.). This indicates that *A. viridis* stands are nitrogen saturated and nitrate leaching does occur at high rates, whereas leaching losses are commonly low in montane coniferous climax forests (zero to 2.2 kg N ha⁻¹ a⁻¹ in *Pinus sylvestris* and *Picea abies* forests in the Swiss Alps; Thimonier et al. 2009). Nitrogen enrichment leads to soil acidification through proton production during nitrification and NH₄⁺ uptake by plants, and also to losses of base cations during leaching of nitrate. Soils under *A. viridis* shrubland have indeed been found to be more acidic than soils in adjacent forest and grassland

(Bühlmann et al., unpubl.; Podrazsky and Ulbrichova 2003). In addition to N losses through leaching, extremely high nitrous oxide emissions of more than $4 \text{ kg N}_2\text{O-N ha}^{-1} \text{ season}^{-1}$ have been measured in *A. viridis* shrubland at 1,500 m a.s.l. in central Switzerland, measured from June to end of September. Adjacent pastures emitted 35 times less of this potent greenhouse gas during the same period (Bühlmann et al., unpubl.).

Suppressed succession towards forest

Vegetation succession starts immediately after land abandonment and natural climax forests establish over time, in particular, below or close to the natural tree line (Tasser and Tappeiner 2002; Wallentin et al. 2008). The presence of *A. viridis* stands prevents such succession towards montane forest. Tree seedlings, for instance of *Larix*, *Pinus* and *Picea*, are unable to establish under *A. viridis* shrubs and its vigorous herbaceous understory (Bischof 1984). In the central Swiss Alps less than 5 % of *A. viridis* shrubland developed into forest within 75 years (Huber and Frehner 2012). Experiences of local farmers show that clear cutting does neither help turning this shrubland into a forest nor does it contribute to reverting the bush into grassland. After clear cutting, *A. viridis* shoots re-sprout vigorously from the rootstock. In addition, the dense understory is maintained over decades due to the high amount of nitrogen in the soil. Thus, without continuous and adapted management, forests cannot develop and replace *A. viridis* thickets once established. Moreover, the encroachment of former grassland by *A. viridis* is also problematic because this shrub does not fulfil the protective function of a montane forest against avalanches, erosion and shallow landslides (Bischof 1984; Caviezel et al. 2014; Tasser et al. 2003).

Economic consequences

The rapid expansion of *A. viridis* does not only affect ecosystem properties at a large scale, but also exerts economic drawbacks. Open landscapes are considered as a valuable natural resource for Swiss tourism worth about 68–79 billion CHF and therefore, contribute substantially to the main source of income especially in mountainous regions depending on tourism (Econcept 2002). Traditionally used agricultural land is diverse and is regarded more attractive by visitors and locals compared to monotonous forests or shrubland (Hunziker 2001; Schirpke et al. 2012). The impenetrable thickets of *A. viridis* shrubland reduce scenic beauty and thus, the touristic value of the landscape.

Depending on climate change and the economic situation, montane and subalpine agricultural land may become more important for forage and food production in the future

(Schirpke et al. 2012). Farms with a high share of montane grassland will suffer less from summer drought, such as that in the year 2003, compared to farms situated exclusively in the lowlands (Finger et al. 2013). It is predicted that drought spells will occur more frequently in the future (Seneviratne et al. 2012) and thus, the importance of these high elevation rangelands for fodder provision will rise. It is very time consuming and labour-intensive to clear *A. viridis* shrubland and consequently, the loss of this valuable montane grassland is almost irreversible. Hence, future generations lose opportunities to adapt to and to mitigate future climatic and economic constraints.

Management options

Preservation of these montane cultural landscapes and stopping further encroachment by *A. viridis* is best achieved by sustainable land use. However, regular haymaking and thereby, suppression of shrub and tree colonisation is labour-intensive and more expensive compared to animal browsing, particularly on steep slopes (Dux et al. 2009). Cultural landscapes can be kept open by goats and special breeds of sheep, which are browsing on the bark of shrubs and trees. Removing the bark and partly injuring the xylem, cause woody plants to die back. Goats and the traditional sheep breeds Engadine sheep (in German: ‘Engadiner Schaf’; commonly raised in Switzerland) and the alpine stone sheep (in German: ‘Alpines Steinschaf’; occurring in southern Germany and Austria; Jaritz 2010) browse on woody plants. The most common sheep breeds (e.g. ‘weisses Alpenschaf’) do not feed on the bark of woody plants at all. Engadine sheep have been shown to be very efficient: after one single summer grazing period, 46 % of *A. viridis* branches died and in recently encroached pastures even 76 % branches died back (MSc project by T. Zehnder, cited in Bühlmann et al. 2013). Furthermore, meat of Engadine sheep is of excellent quality with a low fat content (Willems et al. 2013). Therefore, a ‘value chain’ could easily be generated by meat products of this sheep breed and as a side effect these sheep help to keep old cultural land open. We highly recommend increasing the numbers of goats and Engadine sheep either by means of subsidies or by establishing ‘value chains’ to reduce shrub encroachment and forest expansion, and as a consequence assist in the protection of biodiversity, soil and water quality and scenic beauty in the Alps.

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