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SHORT COMMUNICATION

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

Tobias Bühlmann · Erika Hiltbrunner · Christian Körner

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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 N_2-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)

T. Bühlmann (✉) · E. Hiltbrunner · C. Körner
Department of Environmental Sciences, Institute of Botany, University of Basel, Schönbeinstrasse 6, 4056 Basel, Switzerland
e-mail: t.buehlmann@unibas.ch

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 aquilegiifolium*. 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 NO_3^- 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 NH_4^+ 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 kg N_2O-N ha^{-1} $season^{-1}$ 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: 'Engadinerschaf'; commonly raised in Switzerland) and the alpine stone sheep (in German: 'Alpines Steinschaf'; occuring 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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References

Aber JD, Nadelhoffer KJ, Steudler P, Melillo JM (1989) Nitrogen saturation in northern forest ecosystems. Bioscience 39:378–386. doi:10.2307/1311067

Anthelme F, Grossi JL, Brun JJ, Didier L (2001) Consequences of green alder expansion on vegetation changes and arthropod communities removal in the northern French Alps. For Ecol Manage 145:57–65. doi:10.1016/s0378-1127(00)00574-0

Bätzing W (2005) Die Alpen: Geschichte und Zukunft einer europäischen Kulturlandschaft. Beck, München

Binkley D (1981) Nodule biomass and acetylene-reduction rates of red alder and sitka alder on Vancouver Island, BC. Can J For Res 11:281–286

Binkley D, Sollins P, Bell R, Don S, Myrold D (1992) Biogeochemistry of adjacent conifer and alder-conifer stands. Ecology 73:2022–2033. doi:10.2307/1941452

Bischof N (1984) Pflanzensoziologische Untersuchungen von Sukzessionen aus gemähten Magerrasen in der subalpinen Stufe der Zentralalpen vol 60. Beiträge zur geobotanischen Landesaufnahme der Schweiz. Flück-Wirth, Switzerland

Bobbink R et al (2011) Review and revision of empirical critical loads and dose-response relationships, Proceedings of an expert workshop, Noordwijkerhout, 23-25 June 2010. UNECE Coordination Centre for Effects (CCE), National Institute for Public Health and the Environment (RIVM), Bilthoven, The Netherlands

Brändli U-B (2010) Schweizerisches Landesforstinventar, Ergebnisse der dritten Aufnahme 2004–2006. Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf, Switzerland and Federal Office for the Environment, Bern, Switzerland

Bühlmann T, Hiltbrunner E, Körner C (2013) Die Verbuschung des Alpenraums durch die Grünerle FactSheet. Swiss Academies of Arts and Sciences, Berne

Caviezel C, Hunziker M, Schaffner M, Kuhn NJ (2014) Soil–vegetation interaction on slopes with bush encroachment in the central Alps—adapting slope stability measurements to shifting process domains. Earth Surf Process Landf. doi:10.1002/esp.3513

Compton JE, Church MR, Larned ST, Hogsett WE (2003) Nitrogen export from forested watersheds in the Oregon Coast Range: the role of N_2-fixing red alder. Ecosystems 6:773–785. doi:10.1007/s10021-002-0207-4

David F (2010) Expansion of green alder (*Alnus alnobetula* [Ehrh] K. Koch) in the northern French Alps: a palaeoecological point of view. CR Biol 333:424–428. doi:10.1016/j.crvi.2010.01.002

Dawson JO (2008) Ecology of actinorhizal plants. In: Pawlowski K, Newton W (eds) Nitrogen–fixing actionrhizal symbiosis, vol vol 6. Springer, Berlin, pp 199–234

Dux D, Matz K, Gazzarin C, Lips M (2009) Managing open grassland in the mountain area of Switzerland—what are the costs? Agrarforschung 16:10–15

Econcept (2002) Plausibilisierung Nutzenschätzung Landschaft für den Tourismus

Federal Statistical Office of Switzerland (2013) STAT-TAB: Die interaktive Statistikdatenbank. Neuchâtel, Switzerland, access date 1 April 2014

Finger R, Gilgen A, Prechsl U, Buchmann N (2013) An economic assessment of drought effects on three grassland systems in Switzerland. Reg Environ Change 13:365–374. doi:10.1007/s10113-012-0346-x

Fischer M, Rudmann-Maurer K, Weyand A, Stöcklin J (2008) Agricultural land use and biodiversity in the Alps Mountain. Res Dev 28:148–155. doi:10.1659/mrd.0964

Frost GV, Epstein HE (2014) Tall shrub and tree expansion in Siberian tundra ecotones since the 1960s Global Change. Biology 20:1264–1277. doi:10.1111/gcb.12406

Hiltbrunner E, Schwikowski M, Körner C (2005) Inorganic nitrogen storage in alpine snow pack in the Central Alps (Switzerland). Atmos Environ 39:2249–2259. doi:10.1016/j.atmosenv.2004.12.037

Hiltbrunner E et al (2014) Ecological consequences of the expansion of N2-fixing plants in cold biomes. Oecologia 1–14. doi:10.1007/s00442-014-2991-x

Huber B, Frehner M (2012) Forschungsprojekt Grünerle. Federal Office for the Environment (FOEN), Switzerland

Hunziker M (2001) Welche Landschaftsentwicklung in den Alpen? Die Meinung von Touristen und Einheimischen Hotspot, vol 9

Jaritz G (2010) Montafoner Steinschaf—Das zierliche und flinke. Almtier Der Alm- und Bergbauer 6–7:32–33

Koch B, Edwards P, Blanckenhorn W, Buholzer S, Walter T, Wüest R, Hofer G (2013) Vascular plants as surrogates of butterfly and grasshopper diversity on two Swiss subalpine summer pastures. Biodivers Conserv 22:1451–1465. doi:10.1007/s10531-013-0485-5

Lueth C, Tasser E, Niedrist G, DallaVia J, Tappeiner U (2011) Plant communities of mountain grasslands in a broad cross-section of the Eastern Alps. Flora 206:433–443. doi:10.1016/j.flora.2010.11.007

Myers-Smith IH et al (2011) Shrub expansion in tundra ecosystems: dynamics, impacts and research priorities. Environ Res Lett 6:045509. doi:10.1088/1748-9326/6/4/045509

Niedrist G, Tasser E, Luth C, Dalla Via J, Tappeiner U (2009) Plant diversity declines with recent land use changes in European Alps. Plant Ecol 202:195–210. doi:10.1007/s11258-008-9487-x

Podrazsky VV, Ulbrichova I (2003) Soil chemistry changes in green alder (*Alnus alnobetula* (Ehrh.) C. Koch) stands in mountain areas. J For Sci (Prague) 49:104–107

Rey Benayas JM, Martins A, Nicolau JM, Schulz JJ (2007) Abandonment of agricultural land: an overview of drivers and consequences. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources 2. doi:10.1079/PAVSNNR20072057

Richard L (1967) L'aire de répartition de l'Aune vert (*Alnus viridis* Chaix), vol 5

Richard L (1989) Ecologie des mégaphorbiaies subalpines à aune vert de la Vanoise et des régions environnantes (première parie)—Compréhension de la répartition actuelle des aulnaies. Travaux Scientifiques du Parc National de la Vanoise 17:127–158

Schirpke U, Leitinger G, Tasser E, Schermer M, Steinbacher M, Tappeiner U (2012) Multiple ecosystem services of a changing alpine landscape: past, present and future. Int J Biodivers Sci Ecosyst Serv Manag 1–13. doi:10.1080/21513732.2012.751936

Seneviratne SI et al (2012) Changes in climate extremes and their impacts on the natural physical environment. In: Field CB et al (eds) Managing the risks of extreme events and disasters to advance climate change adaptation, a special report of working groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, pp 109–230

Spehn EM, Liberman M, Körner C (2006) Land use change and mountain biodiversity. Taylor & Francis, UK

Suding KN et al (2005) Functional- and abundance-based mechanisms explain diversity loss due to N fertilization. Proc Natl Acad Sci USA 102:4387–4392. doi:10.1073/pnas.0408648102

Tasser E, Tappeiner U (2002) Impact of land use changes on mountain vegetation. Appl Veg Sci 5:173–184. doi:10.1111/j.1654-109X.2002.tb00547.x

Tasser E, Mader M, Tappeiner U (2003) Effects of land use in alpine grasslands on the probability of landslides. Basic Appl Ecol 4:271–280. doi:10.1078/1439-1791-00153

Thimonier A et al (2009) Does exceeding the critical loads for nitrogen alter nitrate leaching, the nutrient status of trees and their crown condition at Swiss Long-term Forest Ecosystem

Research (LWF) sites? Eur J For Res 129:443–461. doi:10.1007/s10342-009-0328-9

Wallentin G, Tappeiner U, Strobl J, Tasser E (2008) Understanding alpine tree line dynamics: an individual-based model. Ecol Model 218:235–246. doi:10.1016/j.ecolmodel.2008.07.005

Willems H, Kreuzer M, Leiber F (2013) Vegetation-type effects on performance and meat quality of growing Engadine and Valaisian Black Nose sheep grazing alpine pastures. Livest Sci 151:80–91. doi:10.1016/j.livsci.2012.10.015

Zoller H, Bischof N, Erhard A, Kienzle U (1984) Biocoenosen von Grenzertragsflaechen und Brachland in den Berggebieten der Schweiz. Hinweise zur Sukzession, zum Naturschutzwert und zur Pflege vol 12, pp 2–3. Cramer, Berlin