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RESEARCH ARTICLE

# How to achieve the net-zero target? Lessons learned from past transformations

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## Abstract

Transformations–defined as deep, radical, non-linear, multi-dimensional, systemic processes of change–are required to avert serious threats to humanity and the environment. In this study, we have analysed past transformations in Switzerland in four environmental domains, with the aim to draw conclusions for current challenges, such as the net-zero transformation. Firstly, we have conceptualised and defined transformations. Secondly, we have applied and further developed two theoretical frameworks to (i) identify actual transformations in the four domains, and (ii) analyse crucial characteristics of these profound changes. Furthermore, we have examined relevant enabling and hindering factors for transformations. Our study is based on literature review and expert interviews, as well as triangulation workshops to align the collected information. We conclude that providing general blueprints for transformations is not possible due to the complexity and context-specific nature of these processes. However, for the net-zero transformation to be successful, we found that unprecedent efforts are needed with respect to pace, sectors involved, levels of initiative, mindset change in the broader population, and involvement of technology and research. Specifically, we recommend fast action to (i) implement a steering committee combined with citizens' assemblies and cross-sectoral discussion platforms, (ii) encourage different actors to take initiatives at multiple levels, and (iii) enable a broad mindset change across different societal groups.

## Author summary

Heat waves, droughts, biodiversity loss, urban sprawl and floods are just some of the many challenges humanity faces today that must be tackled to prevent greater damage to nature, society, and economy. Current systems (e.g., energy, agriculture, transportation) must change profoundly to ensure a sustainable way of living. To better understand how such profound changes, so-called transformations, occur, how they can be characterized, and what enables and hinders them, we analysed past transformations in four environmental domains in Switzerland. The aim was to draw lessons from these profound changes for the 'net-zero transformation', which is necessary to reach the Swiss net-zero carbon emissions target set for 2050. We found that there is no general recipe for

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successful transformations due to the multiple, complex, and context-specific processes involved. We concluded that—compared to the past transformations–the net-zero transformation needs to occur faster, involve more sectors, be initiated at multiple levels, and be strongly supported by technology and research. Our study offers valuable insights into how transformations occur, and which prerequisites are necessary for the net-zero transformation to be successful.

## 1. Introduction

Profound changes are needed to solve today's global environmental crises and to shift our economies and societies towards sustainability [1]. Such transformations require structural, sometimes disruptive change and different kinds of innovation [2]. Current efforts are not sufficient to simultaneously and effectively mitigate climate change, biodiversity loss and other urgent environmental crises [3]. Immediate actions across different sectors, such as energy, mobility, water or food are needed to address the mentioned environmental and resulting societal crises more comprehensively [4]. Hence, the so-called net-zero transformation, which results from the Paris Agreement on phasing out fossil fuels to reach the 1.5˚C target, overlaps with other transformation necessities and discourses [5–7].

Research has identified various factors that may enable or hinder profound changes. The former include technological, social and institutional innovation, new markets and business opportunities, regulatory measures, leadership, shifting values and also external shocks and crises [8–10]. The latter comprise, inter alia, lock-ins and path dependencies (e.g., formal long-term agreements and contracts, past financial investment), the delayed alignment of international objectives and policies to national policies, and isolated sector-specific policies [11].

Given the magnitude of change required to realise transformations, and hence, the uncertainty of their outcomes, it seems expedient to look at past transformations to improve our understanding of how they may occur and ultimately, of how to bring about future transformations towards sustainability [12]. Additionally, the numerous scientific publications on transformation theories and concepts may help to understand general transformational processes. This extensive body of literature, however, includes relatively few empirical case studies on specific transformations compared to the number of conceptual articles [13]. Our study aims at expanding the knowledge on transformations through analysing the emergence of past successful transformations in four different environmental domains in Switzerland. We focus on the domains biodiversity, forest, landscape, and natural hazards due to their political and societal relevance in Switzerland.

Our study contributes to a better understanding of profound changes by answering the following research questions: (i) How can transformations be conceptualised and characterised? (ii) Which were enabling and hindering factors in past environmental transformations in Switzerland? (iii) Which lessons can be learned from these transformations for the net-zero transformation?

Based on our review of theoretical and empirical articles on transformations, we developed a questionnaire for interviews with experts from the four domains. The analysis of the interviews was complemented by a literature review on the specific environmental domains. We then applied the compiled information to two analytical transformation frameworks, which enabled us to determine crucial characteristics and their role in transformation processes. These insights were mirrored with the challenges of a net-zero transformation.

The article is structured as follows. We first give an overview of theories and concepts and derive a comprehensive definition of transformations. Then we present two frameworks for analysing transformations in practice and identify enabling and hindering factors based on our literature review. After presenting the methods of data collection and analysis, we analyse past transformations in the four environmental domains and compare the results. Afterwards we discuss our results and report on our insights regarding implications for the net-zero transformation, followed by some conclusions.

## 2. Theories and concepts

Transformation research covers a broad field in which different types of knowledge from various disciplines are needed to analyse and understand transformations [12,14]. Research in this diverse field brings about a variety of understandings with respect to transformations, their characteristics, and relevant factors. Thus, we focus our research on a comprehensive definition of transformation, identification of their characteristics, and a better understanding of the processes to determine enabling and hindering factors. Generic frameworks help to grasp, analyse, and compare transformations in different contexts.

### 2.1 Definitions and characteristics of transformations and transitions

The extensive literature on the different perspectives in transformation research [12,15,16] has resulted in manyfold definitions, which make it difficult to distinguish between the terms 'transformation' and 'transition'. We have scanned approximately 60 articles for the definition of the two terms with the most explicit ones being summarised in Table 1 and Table 2. We chose definitions and characteristics based on how frequently they are mentioned in the literature, and on how well they fit to the environmental topics of our study. According to Hölscher

**Table 1. Definitions of transformation (in alphabetical order of authors).** The definitions in bold serve as the basis for our definition (see following paragraphs) and those marked with an asterisk (*) are our translations. Source: own creation.

| Definitions of transformation | References |
|---|---|
| "Deep structural changes in economies, societies and political regimes" | [8] |
| "Radical alteration of systemic interconnections and systems behaviour with fundamentally different sustainability outcomes" | [24] |
| "Reconfigurations of socio-technical systems" | [25] |
| **"Capacity to create fundamentally new systems of human-environmental interactions and feedbacks when ecological, economic, or social structures make the existing system untenable"** | [26] |
| **"'What' [. . .] changes from emergent patterns of change and what are outcomes at a systemic level"** | [17] |
| **"Deep and sustained, nonlinear systemic change, generally involving cultural, political, technological, economic, social and/or environmental processes"** | [22] |
| "A comprehensive societal change [. . .] that includes not only technological, but also political, social, economic, and cultural changes" * | [27] |
| "Fundamental changes in structure, function and relations within socio-technical-ecological systems, that leads to new patterns of interactions (e.g., among actors, institutions, and dynamics between human and biophysical systems) and outcomes" | [12] |
| "Fast, radical change" | [11] |
| "Socio-technical system transformation (or transition) is about changing skills, infrastructures, industry structures, products, regulations, user preferences and cultural predilections. It is about radical change in all elements of the configuration." | [28] |
| "Structural and paradigmatic changes in societies–including cultures, values, technologies, production, consumption, infrastructures and politics" * | [29] |

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**Table 2. Definitions of transition (in alphabetical order of authors).** The definitions in bold serve as the basis for our definition (see following paragraphs). Source: own creation.

| Definitions of transition | References |
|---|---|
| "Non-linear, society-wide processes, with a central role for bottom-up processes of innovation, experimentation, learning and networking." | [9] |
| **"Subset of larger transformation"** | [26] |
| **"Focus on the processes and dynamics producing patterns of change to explain 'how' the non-linear shift from one state to another is supported or hindered."** | [17] |
| "Gradual, continuous process of change where the structural character of a society [. . .] is being transformed. [These] processes [. . .] lead to a new regime with the new regime constituting the basis for further development." | [15] |
| "Large-scale disruptive changes in societal systems that emerge over a long period of decades; [. . .] a threat to existing dynamically stable configurations" | [16] |
| "Qualitative change in the state of a complex system" | [16] |
| "Result of co-evolving processes in economy, society, ecology, and technology that progressively build up toward a revolutionary systemic change on the very long term" | [30] |
| "Fundamental changes in socio-technical systems such as energy, food or transport that aim to address grand challenges" | [31] |
| "Fundamental and long-term transformations of large socio-technical systems guided by sustainability goals and policies" | [10] |
| "Far-reaching changes along different dimensions: technological, material, organisational, institutional, political, economic, and socio-cultural." | [32] |
| "Series of connected and sustained fundamental transformations of a wide range of socio-technical systems in a similar direction." | [33] |

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et al. [17], each term represents a certain manner of describing, interpreting, and supporting a desirable non-linear, radical, and structural change. Which term is employed depends mainly on the research community and the studied system. Researchers who focus on more technical and management aspects, such as [10,18,19], mainly use the term 'transition'. Scholars who study resilience, planetary boundaries, or global change, e.g., [5,20,21] make rather use of the term 'transformation' [17,22].

Overall, there is agreement that transformations and transitions entail a directionality (e.g., towards sustainability), and that involved actors need to agree on such a direction of change [12]. In this respect, Smith et al. [23] mention 'purposive transitions', which are "deliberately intended and pursued from the outset to reflect an explicit set of societal expectations or interests." The direction of change as well as its speed are influenced by the actors' perception of problems and their urgency [10].

Tables 1 and 2 show the great variety of understandings of 'transformation' and 'transition' in the literature. Some definitions refer to the same aspects when defining the two terms (see e.g., [27] in Table 1 and [32] in Table 2) and others define one term by the other (see e.g., [10] in Table 2). Since a clear distinction is difficult to make, we decided to focus on particular differences in definitions and characteristics of 'transformation' and 'transition' in order to provide a clear understanding of the two terms especially for the empirical part of this study. We chose definitions and characteristics based on how frequently they are mentioned in the literature and on how well they fit to the environmental topics of our study.

Several authors provided a useful basis for our definition of both 'transformation' and 'transition' [17,22,26]. Based on their definitions–in bold in Table 1–we define 'transformation' as a *deep*, *radical*, *non-linear*, *multi-dimensional*, *systemic process of change*, *which entails a reconfiguration of skills*, *infrastructures*, *products*, *and regulations*, *alters current human-environment interactions directed towards sustainability*. We define 'transition'–based on the definition in

bold in Table 2–as a *fundamental*, *co-evolutionary*, *long-term process directed towards a change in sub-systems*, and consider that various transition processes all together result in a transformation (as defined above).

## 2.2 Enabling and hindering factors

Transformations are processes, which allow new structures to emerge [26]. Based on our literature review (scanning approximately 70 articles for enabling and hindering factors), we provide a selection of factors enabling new structures in Table 3. Repeatedly mentioned are: (i) a common vision for a more sustainable future among all actors involved in the transformation process; (ii) the identification of regime tensions, which can help open up windows of opportunities for innovations; (iii) the consideration of redistributive and equity conflicts, e.g., how to compensate the 'losers' of declining industries.

Transformations can face various obstacles (see Table 4). The hindering factor mostly frequently mentioned is 'Vested interests' of major stakeholders profiting from the status quo. This factor is often related to lock-in effects and path dependencies, including formal long-term agreements and contracts as well as former financial investments. Further hindering factors are: (i) redistributive conflicts, which can arise during transformations due to a reallocation of resources, capacities, and power; (ii) delayed aligning of international objectives and policies to national and local levels; (iii) limited public awareness and understanding of the need for a transformation, which often results in fear of change or susceptibility for populist propaganda; (iv) compartmentalisation of policies (e.g., transport versus energy policy). For a transformation to be successful, policies are required, which tackle several relevant sectors in

**Table 3. Enabling factors for a transformation/transition (in alphabetical order of authors).** In bold: factors mentioned in at least three articles. Source: own creation.

| Enabling factors | References |
|---|---|
| Steering committee with representatives from all governmental levels | [8] |
| **Democratic transformation: consideration of redistribution and equity issues, i.e., thinking about how to compensate the 'losers' in the declining industry (e.g., through financial support and building new industries)** | [3,9,31] |
| Readiness to explore multiple transformation paths since there is no 'silver bullet' solution | [3,34] |
| Investments in skills, infrastructure and innovation that help shape a transformation | [9] |
| **Identification of regime tensions to open up windows of opportunities for innovations to emerge** | [9,26,35,36] |
| **Common, ambitious vision for a more sustainable future among all actors involved in the transformation** | [2,9,11,36,37] |
| Integral, context-specific policy making: from policy making in isolated units to policy making across units | [9,31] |
| Constant monitoring and re-assessment of the transformation process | [9,11] |
| Willingness of all actors involved in the transformation process to anticipate, experiment, learn and form bridges between networks of societal, economic, and political actors | [9,28] |
| Identification and assessment of transition risks by governments and organisations in order to be aware of vulnerabilities | [36,38] |
| External shocks which can lead to mindset changes (e.g., alterations in socio-economic system, changes in political regimes) | [10] |
| Public pressure | [36] |
| Long-term commitment of influential policy makers to ensure the introduction and durability of policies tackling climate change | [11,36] |
| New set of skills for bridging the social sciences and the natural/technical sciences in order to learn from each other | [28,34] |

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**Table 4. Hindering factors of a transformation/transition towards sustainability (in alphabetical order of authors).** In bold: factors mentioned in at least three articles. Source: own creation.

| Hindering factors | References |
|---|---|
| Redistributive conflicts during the transformation due to a reallocation of resources, capacities, and power | [8] |
| **Vested interests (e.g., of major stakeholders and powerful supporters of the status quo)** | [8,9,11,39] |
| Slow processes of negotiation lowering the level of ambition in the transformation | [9] |
| Limited availability of finances, infrastructure, and policies | [9] |
| Challenges in aligning international objectives and policies to the national and local level | [9] |
| Incapability of radical innovations to trigger changes in the overall system | [31] |
| Tensions between different systems can create new sustainability challenges (e.g., if the forestry or the agricultural sector compete with food production) | [31] |
| Compartmentalisation of policies instead of introducing integrated policies | [31] |
| Lock-ins and path dependency (formal long-term agreements; existing contracts, past financial investments which need to be amortised; powerful supporters of the status quo) | [11] |
| Power of elite groups which can resist income redistribution and taxation | [39] |
| Lack of public awareness and understanding regarding the need of a transformation which leads to a fear of change, vulnerability to populist propaganda or resistance to novel technologies | [39] |

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an integrated way. In our study, we will identify specific enabling and hindering factors for transformations in our four environmental domains.

## 2.3 Frameworks for transformation analysis

In the following, we briefly introduce two analytical frameworks to (i) conceptualise actual transformations, and (ii) determine the role of different transformation attributes. These two frameworks enable a better understanding of past transformations including the mechanisms that brought them about.

The first framework has been developed by Fekete et al. [13]. It characterises transformation processes with three specific steps: 'Triggers', 'Interventions' and 'Adjustments' (see Fig 1). Certain 'Triggers' (e.g., a crisis as initiating event) lead to 'Interventions', defined as a "human-induced change process" [13]. 'Adjustments' are smaller changes made to deal with the change process and to improve it. As a result, the authors refer to transformations as "the superlative of change" [13].

The second framework we use is a transformation typology developed by Linnér and Wibeck [22] (see Fig 2). It clusters transformations according to pace (y-axis) and system (x-axis) into quadrants. The typology can help to distinguish different rationales for

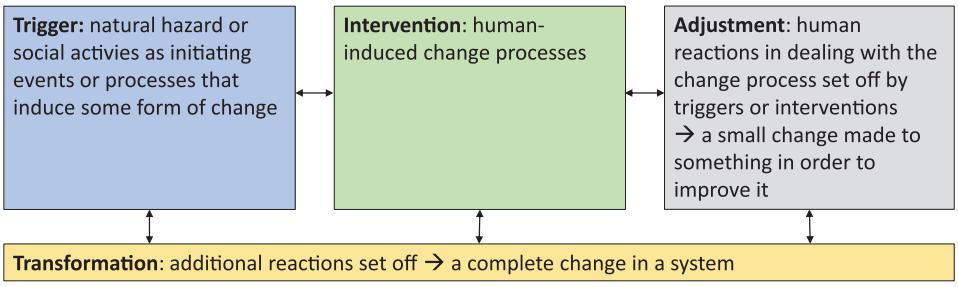


**Fig 1. Analysis framework for identifying actual transformations.** Source: framework of [13] with their descriptions and definitions inserted.

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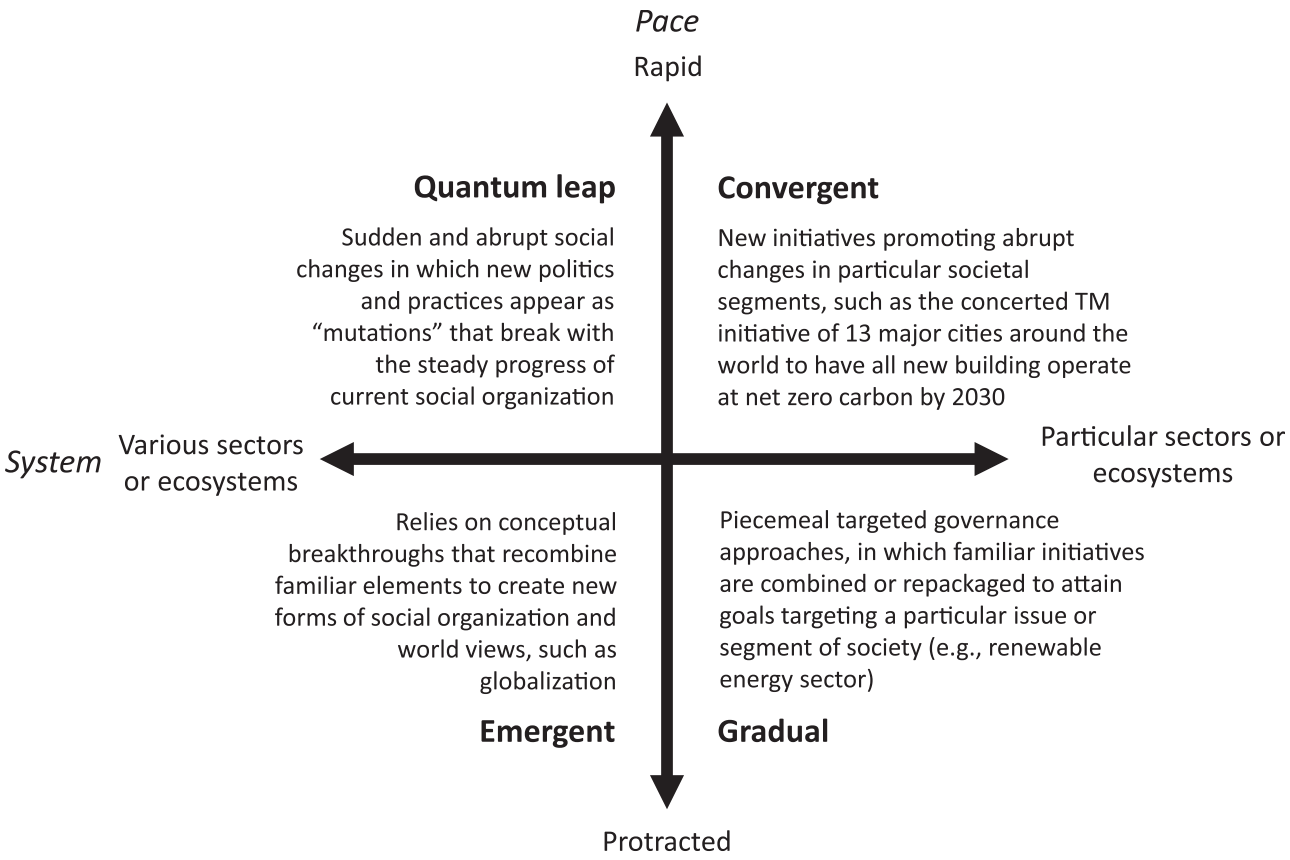


**Fig 2. Typology of societal transformations based on [22], modified.**

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transformations in various sectors from the local to the global level. With respect to 'pace', new transformative elements can be introduced rather rapidly (quantum leap and convergent quadrant) or protracted (emergent and gradual quadrant). Regarding 'system', transformations can occur at different system scales: from one particular sector to various sectors being affected.

In our study we have adapted and applied both frameworks to analyse past transformations in the four environmental domains, which will be presented in Chapter 4.

## 3. Methods

Our study aims at investigating past transformations in four environmental domains in Switzerland to draw lessons for the net-zero transformation. It is based on a systematic review of the international transformation literature, including net-zero transformation, on expert interviews and internal triangulation workshops.

### 3.1 Data collection

The literature review comprised articles about several aspects: first, transformation theories and concepts, such as the definitions and characteristics of transformations, enabling and hindering factors for transformations and frameworks for transformation analysis (see Chapter 2); second, developments in Switzerland in the four environmental domains biodiversity,

forest, landscape, and natural hazards (see below); third, characteristics as well as enabling and hindering factors for the net-zero transformation (see Chapter 5). The four environmental domains were selected due to their importance in the Swiss context: (i) Switzerland is generally rich in *biodiversity* due to topographic and climatic differences [40]. However, the decades-lasting decline of biodiversity [41] has reached alarming dimensions [42]; (ii) *Forests* cover 31% of the country's area and face an increasing demand for important services, such as hazard protection, timber production and recreation [43, 44]; (iii) The *landscape* in Switzerland is well-known for its diverse topography and scenic beauty. At the same time, it is heavily shaped by the environmental, societal and economic developments of the last decades [45]. Especially the so-called 'Mittelland' (central lowlands) is densely populated, with the urban sprawl having started in the 1950s and led to a substantial loss of traditional landscape [46]; (iv) Many Swiss regions are prone to *natural hazards*, such as floods, landslides and avalanches [47], and related policies have a long tradition. All analysed domains have in common that (i) former human decisions and activities had a high impact on their development, (ii) transformations took place due to former challenges, and (iii) they are now facing new challenges due to climate change.

Based on our literature review, we developed questionnaires for expert interviews, which had the aims to identify past profound changes (transformations), to understand the mechanisms behind them as well as to learn about the enabling and hindering factors in these processes. We conducted twelve semi-structured interviews with experts from the four environmental domains (three experts per field) with a duration of 45 to 120 minutes each. The interviews were recorded and transcribed.

Based on our own expertise in the different environmental domains, we then conducted an internal triangulation, where we cross-checked and aligned our interpretations of the interviews, e.g., with respect to the transformations mentioned. Combined with the external expert knowledge gathered through the interviews, the triangulation enabled us to elaborate on the past transformation processes and their attributes, as well as relevant enabling and hindering factors. Ultimately, we decided for two transformations in each domain to be further analysed. The figures and tables in Chapter 4 are the results of these internal discussions, fed by the expert knowledge collected via the interviews as well as the conceptual frameworks from the literature.

## 3.2 Data analysis

We used tables to group the verbal expert statements to conduct a content analysis of the interviews following these steps: (i) investigate the processes of change through applying Fekete et al.'s framework [13]; (ii) identify and rank transformation attributes quantitatively (as introduced by Linnér and Wibeck [22]) through quantifying the verbal statements by numbers, aggregating these numbers to scores and visualising them in spiderweb diagrams; (iii) assess the importance of the enabling and hindering factors from the literature for each transformation.

The steps mentioned above are explained in more detail in the following: first, the framework based on Fekete et al. [13] was applied because it facilitates the identification of actual transformations, which are those deep changes that could serve as a role model for future transformations, e.g., the net-zero transformation. To make the framework more applicable to our study, we defined the two terms 'Adjustment' and 'Transformation' as follows: 'Adjustments' are adaptations or reorganisations of the management system; 'Transformations' describe visible or material changes. Second, the framework of Linnér and Wibeck [22] was applied because it includes attributes that are generally considered as important.

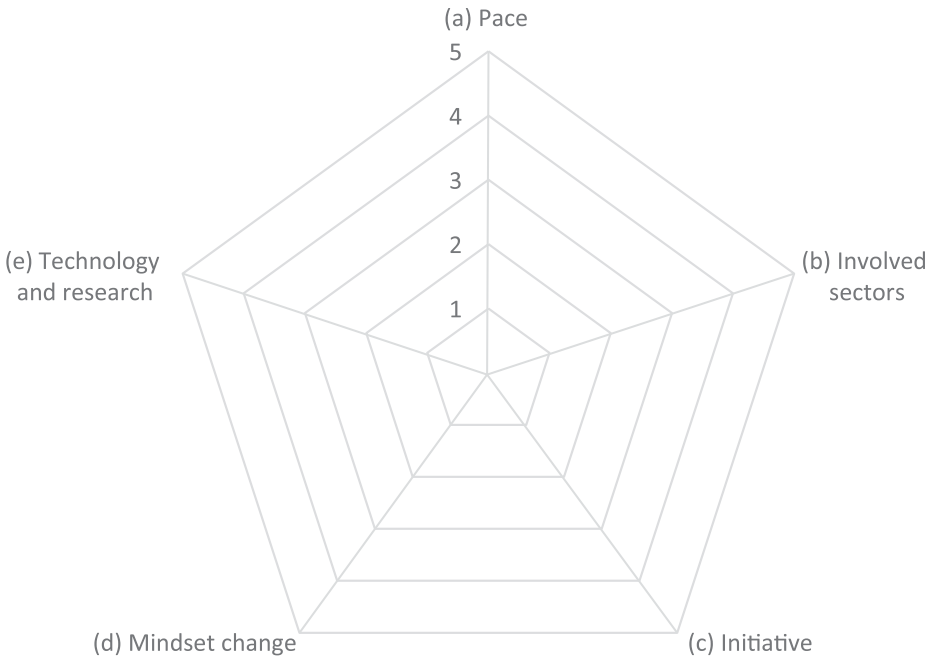


**Fig 3. Spiderweb diagram with five transformation attributes (partly based on [22]).** Source: own creation.

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However, we extended their typology's two attributes 'Pace' and 'System' by another three attributes, and we displayed them in a spiderweb diagram. Hence, it comprises five transformation attributes: (a) Pace, (b) Involved sectors, (c) Initiative, (d) Mindset change, (e) Technology and research. We included these attributes because they were frequently mentioned in the literature and in the expert interviews. 'Pace' refers to how fast a transformation occurred. 'Involved sectors' describes how many sectors were affected by the transformation. 'Initiative' expresses whether the transformation was started/supported by a single level (either bottom-up or top-down) or by multiple levels (bottom-up and top-down as well as in between). 'Mindset change' indicates the degree of such change across different societal groups. 'Technology and research' describe how important these fields were for the transformation. In the spiderweb diagram (see Fig 3), we applied a scoring from one to five to each attribute (see Table 5).

Third, based on the list of enabling and hindering factors for transformations presented in Chapter 2.2, we discussed the importance of each factor that was mentioned by experts in the respective transformation. The experts' statements and the literature review on the domains facilitated the ranking of each mentioned factor from irrelevant to highly relevant.

**Table 5. Description of the scores 1 and 5 for each attribute in the spiderweb diagram.** Source: own creation.

| Attribute | 1 = | 5 = |
|---|---|---|
| Pace | Slow | Fast |
| Involved sectors | Few | Many |
| Initiative | Single level | Multiple levels |
| Mindset change | Limited | Broad |
| Technology and research | Not important | Highly important |

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### 3.3 Drawing lessons for the net-zero transformation

After identifying and characterising past transformations, we drew lessons from these past profound changes for the net-zero transformation. First, we applied the attributes from the spiderweb diagram to the net-zero transformation. Second, we checked the relevance of the enabling and hindering factors identified in the past transformations for the net-zero transformation. This second step was based on the literature on the net-zero transformation and our internal discussions.

The overall basis of this approach is the assumption that there are generic transformation attributes (e.g., 'Pace' and 'System' used by Linnér and Wibeck [22]) as well as enabling and hindering factors (e.g., a common ambitious vision and vested interest, respectively, introduced by EEA [9]) applicable to various transformations. In line with this, lessons are drawn from one transformation (e.g., past environmental transformation) to another (e.g., future net-zero transformation) [12,48–50]).

## 4. Results

### 4.1 Characterising transformations in four environmental domains

**Biodiversity domain.** The biodiversity in Switzerland is steadily declining. This is mainly caused by urban sprawl, intensification of agriculture, spread of invasive species, fragmentation due to infrastructure, intensive use of water bodies, soils and other resources (e.g., quarrying) [40]. Of the profound changes mentioned in the interviews, we recognised two as transformations in the biodiversity domain (see Fig 4).

*BD1: Nationally protected biotopes*: The public's dissatisfaction with the loss of natural areas and the construction of a military site on a bog landscape (Trigger) led the public to initiate the 'Rothenthurm Initiative' (Intervention). It was accepted in 1987 by a public vote and resulted in a strict national protection of bogs based on the establishment of so-called national inventories. Later, three further biotope inventories (dry meadows and pastures, floodplains, and amphibian spawning areas) were established, with the last inventory adopted in 2010 (Adjustment) [51]. At present, about 2.3% of the national surface is protected as national biotopes [52].

*BD2: Regional Nature Parks as a new category of large*, *protected areas*: Triggered by a paradigm shift in nature conservation from protecting specific biotopes and habitats (inventories) towards establishing larger protected areas–including strictly protected areas entirely prohibiting human activities–(Trigger), the Federal Act on the Protection of Nature and Cultural Heritage (NCHA, Bundesgesetz über den Natur- und Heimatschutz) was revised in 2007 (Intervention). This revision adjusted nature conservation from 'inventory politics' towards 'parks politics' (Adjustment). From this point onward, the Federation has supported protected areas of national importance (Pärke von nationaler Bedeutung), which aim at fostering ecological, economic, and social prosperity in new, large and protected areas. More precisely, cantons establishing nationally important nature parks receive financial support from the Federation as long as they fulfil a performance agreement [53]. Eventually, this resulted in the protection of areas as regional nature parks (13.6% of the national surface in 2022 [54]), which became an element of regional development policy. It is not only focused on ecological qualities as it was the case during the 'inventory politics' (BD1) but also on socioeconomic development.

**Forest domain.** Forests cover 31% of the country's area, however they contribute only 0.1% to the Swiss gross domestic product (GDP) [43]. On the other hand, forests provide multiple services to the society. For example, approximately half of the Swiss forest area protects people and infrastructure from natural hazards, such as avalanches, rockfalls, landslides and

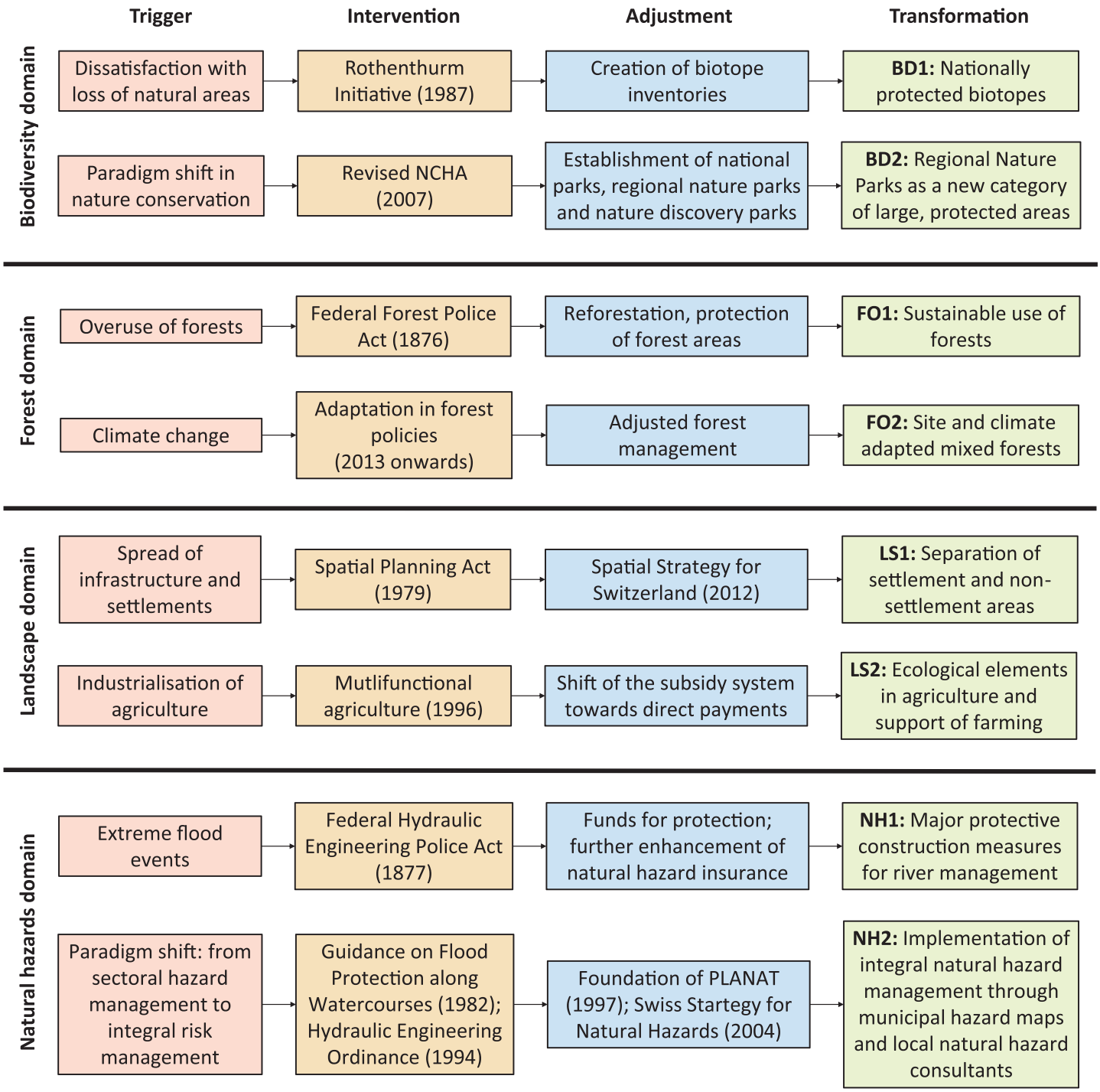


**Fig 4. Transformation processes in the biodiversity, forest, landscape, and natural hazards domain.** Framework based on [13].

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debris flows [43]. The forest sector is organised hierarchically with the overall policy decisions being taken at the national level and concretised and implemented at the cantonal, district, and municipal level. 71% of the forest area is owned by different organisations of the public sector, 29% is in private hands [43]. Of the past profound changes in this domain mentioned

in the interviews, we chose two for further analyses since they deeply changed the forest domain (see Fig 4).

*FO1: Sustainable use of forests*: This process was triggered by a massive overuse of the Swiss forest in the 19th century causing floods and wood shortages (Trigger), which led to the adoption of the first Swiss Federal Forest Police Act (Forstpolizeigesetz) in 1876 (Intervention). The law laid the foundation for policies aiming at protecting and conserving Swiss forests [55] (Adjustments). It introduced the principle of sustainable forestry in Switzerland, that means, not to harvest more wood than what is re-growing [56]. To this end, two elements of this act were the ban on clear cutting and on forest pasture [57].

*FO2: Site and climate adapted mixed forests*: Climate change is inducing an ongoing transformation (Trigger), which so far led to adaptations in forest policies, on both the national and cantonal level (Intervention). On the national level, two articles regarding climate change and forests were added to the Swiss Forest Act [58,59] in 2016. On the cantonal level, initiatives were launched from 2005 on (e.g., a corporation offering CO2-certificates for not harvesting, [60], and cantonal administrations included climate change aspects in their cantonal forest plans, [61] and in their Forest Action Plans, [62]). As a consequence, the Swiss forest management is being adjusted (Adjustments). One element of this process is the tending of young forests to grow trees that are resistant against pests or temperature rise [59,63,64].

**Landscape domain.** The Swiss landscape has been profoundly altered by the country's societal and economic changes of the last decades, which have impacted settlements, infrastructure, agriculture, and forestry. Urban sprawl is widespread with increasing both settlement area and traffic infrastructure. For instance, the Swiss road network grew by 40% from 1972 to 2012. Settlements cover a share of 7.5% of the total country area, with about 60% of this surface being permanently sealed [45]. Agricultural land accounts for 36% of the country's area (2018), however has faced steady reduction since decades [65], with the remaining land being used by increasingly intense production practices [45]. Of the profound changes mentioned by the interview partners, we identified two transformations in the landscape domain (see Fig 4).

*LS1: Separation of settlement and non-settlement areas*: Since the 1950s, infrastructure and settlements have spread across Switzerland, fuelled by a growing population and economy [46]. As a reaction, some cities and municipalities developed zoning plans and building regulations to better control the use of land (Triggers). In 1979, the Spatial Planning Act came into force, which anchored the principle of separating settlement from non-settlement area at the federal level (Intervention). In 1996, the Federal Council adopted the 'Basic features of spatial planning in Switzerland' (Grundzüge der Raumordnung Schweiz), which served as a basis for formulating the non-binding Spatial Strategy for Switzerland in 2012 [66] (Adjustment). The latter provides a framework for spatial planning measures, facilitating decisions for and the collaboration of the Federation, cantons, cities, and municipalities [66].

*LS2: Ecological elements in agriculture and support of farming*: The agricultural industrialisation started at the end of the 19th century and was amplified from the 1960s on by new technologies, policies and increasing agricultural productivity. Since the 1980s, environmental problems of agricultural practice have become obvious and as a reaction, the principle of multifunctional agriculture gained importance at the international level [67]. Also, with the establishment of the World Trade Organization (WTO) in 1995, new international regulations were applied to the agricultural sector (Triggers). In Switzerland, these new regulations as well as societal and political pressure (a total of 10 federal popular votes concerning agriculture took place between 1980 and 1998 [67]) led to the implementation of multifunctional agriculture in the Federal Constitution (Art. 104) in 1996 as a result of a popular vote [67] (Intervention). Multifunctional agriculture in the Swiss context means that agriculture not only

provides food security but also maintains cultural landscapes, natural resources, and decentralised settlements [67, 68]. In 1999, an agri-environmental performance record became preconditional for farmers to receive direct payments (Adjustment) [68].

**Natural hazards domain.** Many parts of Switzerland are prone to natural hazards such as floods, landslides, rock falls, avalanches, and storms. With ongoing climate change, these risks increase due to the more frequent occurrence of extreme events as well as the melting of permafrost, which destabilises rocky slopes [47]. Despite increased protection measures against natural hazards, the risk of high damages to the population and tangible assets persists. The increasing size of the population and the extension of tangible assets intensifies the need for effective protection measures even more [47]. We identified two transformation processes out of the profound changes mentioned in the interviews in the natural hazards domain (see Fig 4).

*NH1: Major protective construction measures for river management*: Frequently occurring extreme events, such as floods during the 19$^{th}$ century and especially the major flood event of 1868 (Trigger) [69,70] led to a shift of responsibilities from the cantons to the Federation and the adoption of the Federal Hydraulic Engineering Act (Wasserbaupolizeigesetz) in 1877 (Intervention) [70]. Consequently, large-scale river correction measures were funded intensively until 1950 [69], such as the Rhone correction in 1888 and parts of the Jura water correction from 1936–39 [70]. Furthermore, insurances against natural hazards, e.g., damages through floods, became part of insurance policies to cover elementary damages after 1950 (Adjustments) [71].

*NH2: Implementation of integral natural hazards management through municipal hazard maps and local natural hazards consultants*: In the second half of the 20$^{th}$ century, natural hazards management became more integral. It did not only focus on damage avoidance by engineering solutions but started to involve stakeholders and anticipatory planning measures, such as retention areas [72]. This paradigm shift from pure hazard prevention to integral risk management (Trigger) triggered the development of the first Guidance on Flood Protection along Watercourses (Wegleitung 'Hochwasserschutz an Fliessgewässern') in 1982 and led to the adoption of the Hydraulic Engineering Ordinance (Wasserbauverordnung) in 1994 (Intervention). The latter obligates the cantons to designate hazard zones, and to include them in the cantonal land-use planning [73]. The paradigm shift manifested in the establishment of PLANAT (Federal Council's Advisory Board for Natural hazards) in 1997 [69], which laid the foundation for the development of the first 'Protection against Natural Hazards Strategy' in 2004 (Adjustments) [74]. Overall, natural hazards management has been integrated in spatial planning and municipal development respectively [72], and resulted in the adoption of hazard maps indicating hazard-prone areas. Furthermore, local natural hazards consultants were trained and introduced by the Federal Office for the Environment (FOEN) in order to strengthen preventive measures and to harness and foster the local knowledge regarding natural hazards [75].

## 4.2 Analysing transformation attributes

Fig 5 visualises the five transformation attributes (introduced in Chapter 3.2) and the respective scores (1–5) for all the transformations in each environmental domain. In Table 6, we explain why we assigned the respective attribute scores. In the following, we present the general observations concerning the particular attribute scores. First, we outline the similarities and differences between the transformations *within* each environmental domain (intra-domain comparison). Second, we compare the transformations *across* the environmental domains (inter-domain comparison).

**Intra-domain comparison.** The scores of the *biodiversity* domain indicate that the two transformations are most alike in terms of the attribute 'Pace': both occurred rather quickly


**Fig 5. Spiderweb diagrams showing the attributes' scores of all the transformations investigated in this study.** Each spiderweb diagram represents one environmental domain. The attribute scores from 1 to 5 can be described as follows: (a) Pace: 1 = slow vs. 5 = fast; (b) Involved sectors: 1 = few vs. 5 = many; (c) Initiative: 1 = single level vs. 5 = multiple levels; (d) Mindset change: 1 = limited vs. 5 = broad; (e) Technology and research: 1 = not important vs. 5 = highly important. Source: own creation partly based on [22].

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(4). The respective changes have been initiated rather from a single level (1/2) with a moderate 'Mindset change' (2/3). 'Technology and research' were of little importance (1/2). The processes differ the most regarding the number of 'Involved sectors': in BD1 there were only some sectors involved (2), whereas the score was higher (4) in BD2. Overall, the two biodiversity transformations are rather different with both transformations scoring higher than the other in two out of five attributes.

The *forest* transformations occurred in rather moderate terms, i.e., there are no attributes with a score of 4 or 5 (see Fig 5). The 'Pace' can be described as rather slow (2) and the number

**Table 6. Short description and explanation of the attribute scores (numbers in brackets) as visualised in the spiderweb diagrams in Fig 5.** Source: own creation.

| Transformation | Attribute | | | | |
|---|---|---|---|---|---|
| | **(a) Pace** | **(b) Involved sectors** | **(c) Initiative** | **(d) Mindset change** | **(e) Technology and research** |
| BIODIVERSITY | | | | | |
| **BD1: Nationally protected biotopes** | Rather fast because of legal obligation for inventories of bogs and other biotopes (4) | Nature conservation and agriculture (2) | Federal popular initiative (1) | Agricultural practice, nature conservation administration, civil society (3) | Biotope maps developed by ecological research (2) |
| **BD2: Regional Nature Parks as a new category of large, protected areas** | Rather fast due to legal opportunity and financial support for regional nature parks (4) | Nature conservation, agriculture, forestry, tourism (4) | Federal administration, environmental NGOs (2) | Federal administration for landscape conservation, rural municipalities (2) | Not important (1) |
| FOREST | | | | | |
| **FO1: Sustainable use of forests** | Rather slow because of slow 're-composition of the forest' (2) | Forestry and agriculture (2) | Federal administration (1) | Forest administration and practice, federal politics (2) | Not important (1) |
| **FO2: Site and climate adapted mixed forests** | Rather slow because of slow growth of planted trees (2) | Forestry and nature conservation (2) | Federal and cantonal administration, forest practice, research (3) | Forest administration and practice, environmental NGOs, forest research, forest visitors (3) | Climate forest adaptation research (2) |
| LANDSCAPE | | | | | |
| **LS1: Separation of settlement and non-settlement areas** | Slow and gradual because of incremental processes in landscape domain (2) | Agriculture, forest, nature and landscape conservation, natural hazards, spatial planning (4) | Federal and cantonal administration, landscape and cultural heritage NGOs, various planning associations (4) | Spatial planning administration, civil society, landscape and cultural heritage NGOs (3) | Proposals on planning schemes by spatial planning research (2) |
| **LS2: Ecological elements in agriculture and support of farming** | Rather fast because of effective incentives through agricultural policies (4) | Agriculture, food, trade policies, nature and water conservation (3) | Federal administration, various federal popular initiatives (2) | Agricultural administration and practice, civil society (2) | Agricultural research on support schemes for farmers (2) |
| NATURAL HAZARDS | | | | | |
| **NH1: Major protective construction measures for river management** | Rather slow due to slow planning and constructions processes (2) | Natural hazards management, spatial planning, agriculture, construction (3) | Federal and cantonal administration (2) | Natural hazards administration, civil society, municipalities (2) | Hydrological and civil engineering, protection technologies (4) |
| **NH2: Implementation of integral natural hazards management through municipal hazard maps and local natural hazards consultants** | Medium pace due to hesitant municipalities and slow spatial planning processes (3) | Natural hazards management, spatial planning, agriculture, forestry (3) | Federal, cantonal, and municipal administration (3) | Municipal natural hazards and spatial planning administration, civil society (2) | Natural hazards research (2) |

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of 'Involved sectors' was low (2). The two transformations differ the most regarding the attribute 'Initiative', which took place at a single level top-down (1) in FO1, while at multiple levels (3) in FO2. Overall, the two forest transformations show quite similar attribute levels with FO2 scoring slightly higher than FO1 in three out of five attributes.

The *landscape* transformations differ most in terms of 'Pace', with LS1 being considerably slower (2) than LS2 (4). On the other hand, LS1 has more 'Involved sectors' (4) and multiple levels of 'Initiatives' (4). Nevertheless, most scores are at level 2, which indicates rather moderate transformations, especially considering LS2. The two transformations are most alike regarding the attribute 'Technology and research', which was of little importance (2) in both cases. Overall, the landscape transformations are rather different with LS1 scoring higher in three out of five attributes.

The *natural hazards* transformations do not show strong swings of attribute scores either (no attribute scores a 1 or 5). The scores assigned the most are 2 and 3. The two transformations are most alike regarding the medium number of 'Involved sectors' (3) and the moderate 'Mindset change' (2). The biggest difference between the two transformations can be found in 'Technology and research', being of great importance (4) for NH1 and of lower importance (2) for NH2. Overall, the two transformations are alike regarding several attributes with NH2 scoring slightly higher in two out of five attributes.

**Inter-domain comparison.**

*(a) Pace*: The transformations in the forest and natural hazards domain were comparably slower than those in the landscape and biodiversity domain. The transformations BD1 and LS2 were accelerated by popular initiatives. Both biodiversity transformations happened fast, which can be explained by legal opportunities (public votes) taken by the respective entities, and the readily available financial support by the government. LS1 happened rather slowly and is–like FO2, LS2 and NH2–still ongoing.

*(b) Involved sectors*: Both transformations in the forest domain involved the smallest number of sectors compared to the other domains. In contrast, transformations in the landscape (LS1) and biodiversity (BD2) domain involved rather many sectors which is due to the domain's many stakeholders.

*(c) Initiative*: One of the transformations in the landscape domain (LS1) received the highest score of levels involved, followed by the forest (FO2) and natural hazards (NH2) domain. In contrast, FO1 and BD1 received the lowest score. Most transformations were initiated by multiple levels, but all showing a tendency of top-down steering.

*(d) Mindset change*: All environmental domains show the same moderate scores concerning this attribute, indicating that all transformations required a mindset change only across a limited number of societal groups. In the natural hazards domain, the mindset change occurred exclusively across a few groups.

*(e) Technology and research*: Technology was only of little importance regarding almost all transformations. The elevated scores were almost exclusively based on the research component. There is one exception in the natural hazards domain: in NH1 technology (mainly engineering) was substantially important. In FO1 and BD2, neither technology nor research was important because first, there was no technical assistance required for enabling any of the two transformations and second, research had little to no influence on shaping the policies required to enable these transformations.

Overall, we found that strong deflections in attribute scores are rare, particularly towards the upper end of the scale. The maximum score is 4, achieved only once by the attributes 'Technology and Research' (NH1) and 'Initiative' (LS1), twice by 'Involved Sectors' (LS1 and BD2), and three times related to 'Pace' (LS2, BD1 and BD2). The score reached by far most often is 2, indicating that the majority of the investigated transformation processes were moderate with respect to the applied attributes.

## 4.3 Identifying enabling and hindering factors

Based on the enabling and hindering factors found in the literature, mentioned in the interviews or to the knowledge of the authors, we took up those being relevant for our

environmental transformations. In the following, we present these factors, graded as irrelevant, relevant, or highly relevant. More information on specific transformations can be found in Chapter 4.1.

**Enabling factors.** Table 7 lists the nine most pivotal enabling factors for the past eight Swiss environmental transformations we investigate in this paper and their specific relevance in each transformation.

Two enabling factors were relevant in all eight transformations: 'Common, ambitious vision' and 'Steering committee/governmental levels involved'. This implies that having a common ambitious vision is crucial to guide profound changes and to develop shared values, which are essential for a successful transformation [9]. Formulating specific long-term objectives and visions improves policy formulations [76] and, in consequence, increases the chances of the policy to be implemented effectively. A steering committee consisting of representatives from all governmental levels–the federal, cantonal, and municipal level–is tasked with bringing about a transformation in which different interests are considered.

Four enabling factors were of high relevance in five transformations: 'External shocks', 'Public pressure', 'Urgency to act' and 'Investments in skills, infrastructure and innovation'. 'Urgency to act' dominates in the forest domain (e.g., climate change threatens forest in FO2) and natural hazards domain. The latter is complemented by 'External shocks' (e.g., extreme flood events in the 19$^{th}$ century in NH1) and 'Investments in skills, infrastructure, and innovation' (e.g., engineering solutions combined with stakeholder involvement and anticipatory planning measures in NH2). This finding can be explained by the visible damage caused by natural catastrophes in these domains, e.g., forest fires or floods. In the other domains, damages are not visible in a similar way, and do not threaten the population directly. 'Public pressure' was identified as highly important in one of the biodiversity transformations (BD1). In this case, it was a federal popular initiative that fuelled the transformation after being triggered by the societal dissatisfaction with the loss of natural areas. With respect to transformations with more than one factor being of high relevance, we identify one, namely NH1 with three highly important factors.

The factor 'Multiple paths instead of silver bullet solution' was assigned to only three transformations, indicating a limited relevance. This can be seen as a consequence of the narrow focus of the transformations in our specific domains. The broader the scope of the transformation, and the more sectors and societal groups are involved, the more paths and approaches must be used to reach the target.

**Table 7. Importance of enabling factors in the eight transformations investigated.** Blank = irrelevant, * = relevant, ** = highly relevant. BD1 and BD2: Biodiversity transformation 1 and 2; FO1 and FO2: Forest transformation 1 and 2; LS1 and LS2: Landscape transformation 1 and 2; NH1 and NH2: Natural hazards transformation 1 and 2. Source: own creation.

| Enabling Factors | BD1 | BD2 | FO1 | FO2 | LS1 | LS2 | NH1 | NH2 |
|---|---|---|---|---|---|---|---|---|
| External shocks | | | * | * | | | ** | * |
| Public pressure | ** | * | | | * | * | * | * |
| Urgency to act | | | ** | ** | * | * | ** | * |
| Common, ambitious vision | * | * | * | * | * | * | * | * |
| Steering committee/governmental levels involved | * | * | * | * | * | * | * | * |
| Integral, context-specific policy making | | * | * | * | * | * | * | * |
| Investments in skills, infrastructure and innovation | | * | * | * | | * | ** | ** |
| Constant monitoring and re-assessment | * | * | * | * | * | * | | * |
| Multiple paths instead of silver bullet solution | | * | | * | | * | | |

https://doi.org/10.1371/journal.pstr.0000068.t007

**Table 8. Importance of hindering factors in the eight transformations investigated.** Blank = irrelevant, * = relevant, ** = highly relevant. BD1 and BD2: Biodiversity transformation 1 and 2; FO1 and FO2: Forest transformation 1 and 2; LS1 and LS2: Landscape transformation 1 and 2; NH1 and NH2: Natural hazards transformation 1 and 2. Source: own creation.

| Hindering Factors | BD1 | BD2 | FO1 | FO2 | LS1 | LS2 | NH1 | NH2 |
|---|---|---|---|---|---|---|---|---|
| Compartmentalisation of policies/sectoral thinking | * | * | | | ** | * | | |
| Federal structure | * | * | * | | ** | * | | |
| Lack of public awareness and understanding | | * | | | | | | |
| Public opinion | | * | | | | | | |
| Vested interests/current perception | * | * | * | | * | * | | |
| Redistribution conflicts | * | * | * | | * | * | | * |

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**Hindering factors.** Table 8 displays the six most pivotal hindering factors for our investigated transformations and their specific relevance in the respective transformations. There was no hindering factor being of relevance in all the eight transformations, and for two transformations no hindering factors could be identified at all (FO2, NH1).

'Redistributive conflicts' is the factor being relevant to six out of eight transformations. This result does not come as a surprise given that profound changes often cause structural upheavals in the economy and society. Only in two transformations, FO2 and NH1, this factor is of no relevance. Interestingly, these two transformations did not face any hindering factor at all. Thus, they can be seen as non-representative exceptions, as they combine a narrow focus involving only very few sectors and public parties on the one hand with many and strong enabling factors on the other.

Two factors were highly relevant in one transformation (LS1): 'Compartmentalisation of policies/sectoral thinking' and 'Federal structures'. The two factors are closely related since the federal structures in Switzerland fuel the compartmentalisation of policies. Both factors posed a crucial hinderance in LS1. This can be explained by the fact that there was no legal basis for spatial planning in Switzerland at that time. Hence, the Federation planed and decided on a sectoral basis how the land was to be used and by whom [77]. Furthermore, the country's federal administrative structure promoted the development of sectoral thinking. Consequentially, every involved federal office had claims for areas. A nationwide legal structure was missing that would distribute and assign areas to different sectors and purposes [78].

Both, 'Lack of public awareness and understanding' and 'Public opinion' were relevant for only one out of eight transformations (BD2). BD2 is special in the sense that all hindering factors were important for it. This might be due to the fact that there were many involved sectors and hence the possibility of hindering factors becoming important increases. The results suggest that for a transformation involving many sectors these factors should be taken into consideration.

Our comparison clearly shows that the enabling factors were important in many more transformations than the hindering factors. This is not surprising since all eight transformations were overall successful, i.e., the hindering factors were not as powerful as to stop or to hinder the transformation.

## 5. Discussion

In the following, we first discuss the applied frameworks, and second elaborate the relevance of our results for net-zero transformations. Third, we point out some limitations of our study.

## 5.1 Conceptualisation of transformations

The first research question focused on how transformations can be conceptualised. To answer this question, we adapted and applied the frameworks of Linnér and Wibeck [22] and Fekete et al. [13]. This enabled us to (i) identify important characteristics of transformations, (ii) analyse different past transformations, and (iii) better understand the mechanisms behind them. Extending Linnér and Wibeck's four quadrant framework [22] to a spiderweb diagram with five attributes allowed us first, to better identify the differences among the transformations in different environmental domains, and second, to specify the degree to which the attributes contributed to the transformation process. Using Fekete et al.'s framework [13] for identifying actual transformations helped us to focus on key elements of transformation processes and their relationships. Though, we must concede that our domain-specific results cannot be easily transferred or generalised. For example, the contribution of 'Technology and research' to the transformations we analysed was relatively small. But this was rather due to our focus on transformations in environmental domains and would certainly look different for other more technically oriented domains, such as the transformation of the energy sector towards net-zero carbon emissions. Overall, the two frameworks proved to be suitable to conceptualise transformation processes and to bring insightful aspects to the fore.

Our methodological approach of complementing a literature review with expert interviews and internal triangulation enabled us to include various perspectives on transformations. However, a bias might be caused by the rather small number and subjective view of the interviewees [79]: different people emphasise different aspects, which can disguise the actual triggers, interventions and adjustments of the transformation processes. To reduce this bias, we held regular internal triangulation workshops, aimed at specifying and putting into context the different aspects provided by the expert interviews.

The results of the literature review on transformation concepts are multifaceted, not least due to the high number of articles, focusing on diverse transformation aspects and using different definitions of the terms 'transformation' and 'transition'. We acknowledge that if transformations are understood as profound, radical, non-linear processes concerning more than one domain [24,29], the profound changes identified in our specific environmental domains might rather be called transitions, defined as context-specific processes of change in sub-systems [26]. Nevertheless, the interviewed experts definitely perceived these processes as profound changes in the respective environmental domain so that the term 'transformation' may be justified. Thus, which term to use is highly context-specific and depends on the particular perspective.

## 5.2 Assessment of transformation attributes for net-zero transformations

A further research question dealt with the lessons to be learned from past transformations for net-zero transformations. The latter require fundamental changes in many sectors that are causing carbon emissions, such as energy, transportation, production and land-use systems, including urban areas [2]. Thus, the changes required to achieve the net-zero target until 2050 need to (i) be realised at a high pace and, (ii) occur across various sectors, (iii) involve multiple policy levels, (iv) lead to a change in mindset and behaviour in all parts of society, and (v) be fed by technology and research [2,9,22,80–83]. Consequently, the requirements of the net-zero transformation exceed those of our past environmental transformations with respect to all attributes. Thus, in our view, there is evidence for assigning a score of 5 to each attribute for a net-zero transformation (see Fig 6).

The greatest differences between the transformations we analysed and net-zero transformations refer to the attributes 'Mindset change' (d) and 'Technology and research' (e). As the WBGU [2] puts it: "[the net-zero transformation] is both about [the] reorganisation of markets

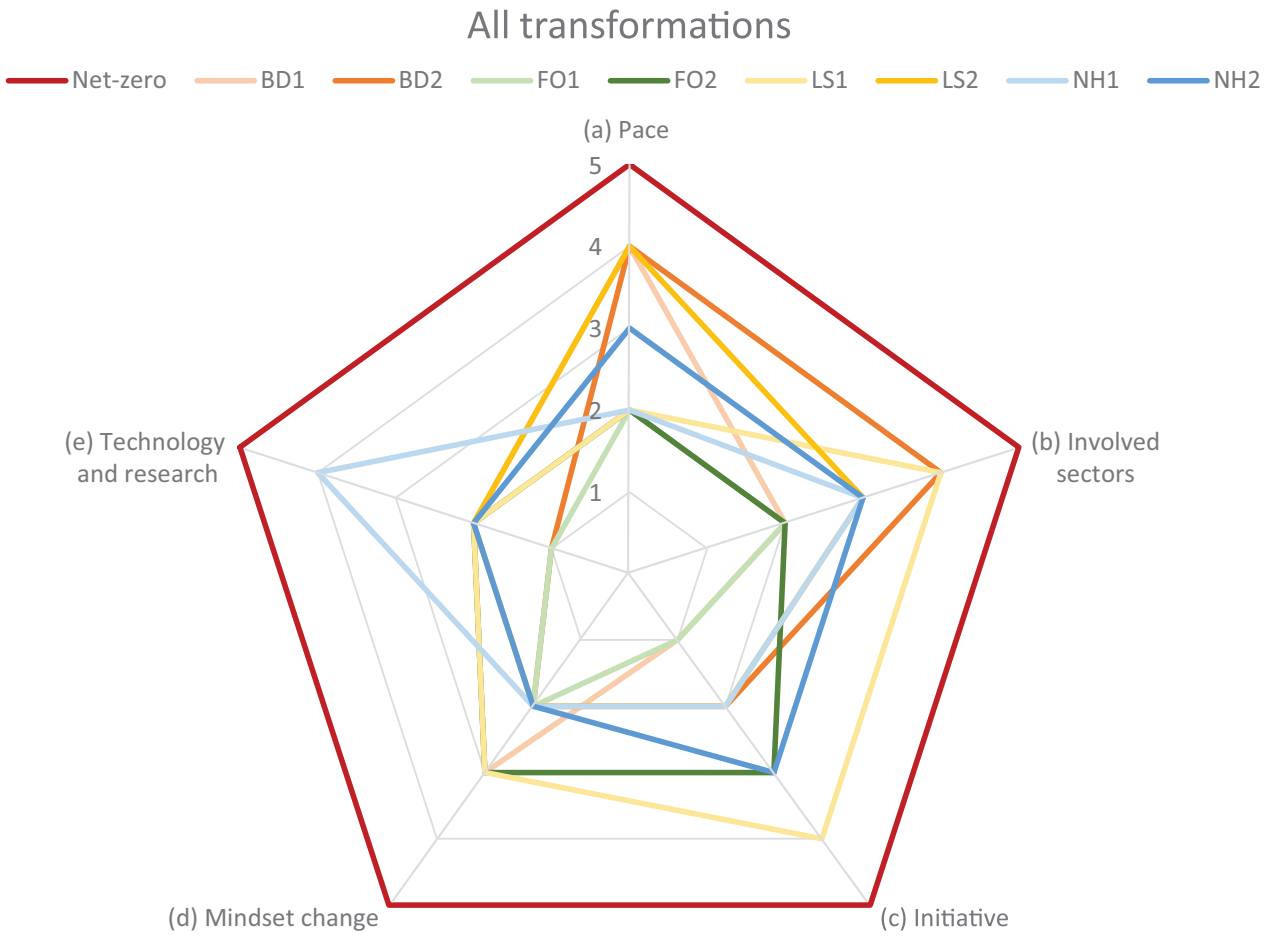


**Fig 6. Spiderweb diagram showing the attribute scores for the four environmental and net-zero transformations.** Source: own creation.

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and the restructuring of institutional systems and, in equal measure, 'hard' technological innovations and 'soft' socio-cultural mindset changes.". This means, for the net-zero transformation to be successful, the mindset change needs to go beyond specific groups, covering the whole society. 'Technology and research' (e) were highly important only in one of the transformations of the natural hazard domain, i.e. for the construction of protective measures. For the net-zero transformation this attribute is of higher importance, due to the fact that it is needed in diverse technological realms, e.g., in renewable energies, carbon capture and storage (CCS), energy saving technologies etc. [2,84].

Regarding the attribute 'Initiative' (c), the landscape transformation (LS1) and net-zero transformations display a relatively high similarity. In LS1, the initiative originated from multiple levels: the federal, cantonal, municipal level as well as cultural-heritage NGOs and various associations initiated the process of change. However, the net-zero transformation requires even more levels to take the initiative. It is necessary to develop and implement a "'multilevel architecture' politics of global governance, as the forthcoming changes concern all political action levels, from local through national to global level" [2].

Overall, we recognise that the past transformations we investigated are much less comprehensive compared to net-zero transformations. For these to be successful the attributes should

not only have high scores, but the changes should also be synchronised, i.e., reforms are required to happen in parallel, while taking all cross-sectoral relations and policy levels into account [2].

## 5.3 Evaluation of enabling and hindering factors for the net-zero transformation

**Enabling factors.** The research question regarding the lessons learned extends also to the enabling and hindering factors (see Table 9). Our results show that the enabling factors 'Common ambitious vision' and 'Steering committee/governmental levels involved' were the sole factors that were relevant to all transformations investigated. When it comes to the Swiss net-zero carbon emissions target by 2050, it can be interpreted as a 'Common ambitious vision'. The implementation of a steering committee, ideally with representatives from all governmental levels, is a further important enabling factor [8], enhancing the chances of successfully implementing transformative measures. Interestingly, this factor does not play a similarly important role in the general transformation literature. Nevertheless, we suggest taking this factor into consideration when analysing future profound changes in countries with a federal or multilevel governance system, such as Switzerland. A further enabling factor for the net-zero transformation being highlighted in the literature is a 'Strong political will to implement effective policies' [6], though seemingly it is not relevant in the transformations investigated. This factor is closely related to and feeds into 'Steering committee/governmental levels involved', with the potential to foster profound changes.

The enabling factors of high relevance in the environmental transformations we analysed are 'External shocks', 'Public pressure', 'Urgency to act' and 'Investments in skills, infrastructure and innovation'. For the net-zero transformation to be successful, all four factors are highly important: shocks evoked by climate change (e.g., floods, droughts, wildfires etc. [85]), a high awareness of the urgency to act combined with the public pressure to replace fossil fuels [6], and to invest in new technologies, infrastructures, and skills [2,86].

The enabling factor being least relevant for the environmental transformations we analysed is 'Multiple paths instead of silver bullet solution'. Nevertheless, multiple paths are needed in case of the net-zero transformation, in which measures must be combined across sectors (e.g., energy, transportation, agriculture, consumption etc.) and at multiple levels (from the individual person to the international community) [2,9,39].

**Hindering factors.** We identified 'Redistributive conflicts' as the most frequent factor hindering transformations. With respect to the net-zero transformation, the literature mentions the loss of employment and invested capital, which may trigger redistributive conflicts through phasing-out industries as a major hindering factor [87,88]. Thus, our results are in

**Table 9. Enabling and hindering factors for net-zero transformations.** Source: own creation.

| Enabling factors | Hindering factors |
|---|---|
| Common ambitious vision | Redistributive conflicts |
| Steering committee representing all governmental levels | Compartmentalisation of policies/sectoral thinking |
| Strong political will to implement effective policies | Federal structures |
| External shocks | Lack of public awareness and understanding |
| Public pressure | Public opinion |
| Urgency to act | |
| Investments in skills, infrastructure and innovation | |
| Multiple paths instead of silver bullet solution | |

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line with other findings emphasising the consideration of equity aspects in the net-zero transformation [50].

We identified two further hindering factors of high relevance: 'Compartmentalisation of policies/sectoral thinking' and 'Federal structures'. Regarding the net-zero transformation, sectoral thinking as well as federal structures can be major hindering factors. Lacking communication and coordination between different federal levels (federation, cantons, municipalities in Switzerland) can seriously hamper the implementation of policies aiming at the net-zero target [87]. Thus, it is important to develop a climate strategy comprising many different sectors, interests and policy levels to reduce the risk of a failure [87].

Both, 'Lack of public awareness and understanding' and 'Public opinion' were least relevant for our investigated transformations. With respect to the net-zero transformation, social acceptance, i.e., public awareness and understanding, is an important condition for the transformation to be successful [82]. The same holds for the public opinion, together with social movements and policy makers who aim for this purposive transformation [6].

### 5.4 Limitations

The scope of enabling and hindering factors relevant for the net-zero transformation goes beyond those identified in the environmental domains we analysed. One important hindering factor not discussed in this paper is path dependency. Processes, which are path dependent, are driven by formerly promising economic and social circumstances as well as increasing economies of scale. These processes anchor technically and environmentally disadvantageous institutional, technical and behavioural systems, and hence prevent a large-scale system change [83]. Further, we did not deal with lock-in effects. They are defined as commitments to (i) institutions (mindsets, beliefs), (ii) certain missions and identities of an industry, (iii) existing, incumbent technologies, and (iv) industry-specific regulations brought about by compliance measures [6]. In the context of net-zero transformations, carbon lock-ins are evoked. They may concern technologies, infrastructures, institutions, and individual behaviour [83]. Path dependency and resulting lock-in effects can severely hamper the net-zero transformation. They should, thus, be additionally taken into account when designing and implementing this fundamental change.

For future research, investigating not only successful but also failed transformations could increase the understanding of specific hindering factors for transformations as well as the dangers and implications of failure. Besides these conceptual limitations, we also identify methodological limitations. First, we chose four environmental domains due to our own expertise and importance to Switzerland while acknowledging that other domains would be interesting to investigate as well (e.g., energy, mobility, housing). Second, our choice of domains and case studies might limit the general applicability of our results. Third, the number of interviews conducted was rather small. However, we were interested in interviewing experts with profound and long-standing experience in their fields. Obviously, the number of people with such expertise is rather small. Nevertheless, the interviews provided valuable insights into past transformations in the domains and cases we investigated, supplemented by our own expertise.

## 6. Conclusions for net-zero transformations

Our analysis of past transformations shows that they do not occur by chance and often result from multiple causes or triggers. Even looking into specific environmental domains indicates that transformations are complex, cross-sectoral, and profound multi-level changes embedded in broader discourses involving different actors. Our analysis clearly demonstrates that–based

on knowledge about past transformations–it is not possible to provide a blueprint for successful current or future transformations. Nevertheless, our study offers insights on how to design transformations, and which relevant attributes as well as enabling and hindering factors to consider. Regarding net-zero transformations in general, establishing a steering committee seems crucial as they require actions and initiatives in different sectors, at multiple administrative levels, and involve highly diverse actors. Such a committee could be led by a specific public 'authority for transformations', which is to be supplemented by citizens' assemblies [89,90] (representing the society) and cross-sectoral discussion platforms (representing different sectors). This supplementation may additionally encourage initiatives by different actors at multiple levels. Net-zero transformations are not only about revising energy or climate politics. They rather require a profound change of various policies and the introduction of net-zero oriented missions and commitment at all levels and in all sectors and domains, including business, politics, and society. This fundamental challenge can only be overcome by a mindset change across different societal groups and sectors, fostering the acceptance of new energy technologies and the adaptation of actors' behaviour, e.g., with respect to production, consumption and infrastructure. Compared to past transformations, all these changes have to occur at a high pace since the net-zero target is set for 2050.

To better understand the required changes in the realms of utmost concern for net-zero transformations further research is needed. We recommend to focus on the following research questions: (i) What are the relevant sector- and context-specific enabling and hindering factors for net-zero transformations?; (ii) What are the preconditions for a broad change in mindsets, paradigms and discourses?; (iii) How do supporting initiatives emerge on the ground, e.g., by grassroot/niche initiatives or social innovation, and how can they be supported and upscaled?; (iv) How to design policies or policy mixes to mainstream net-zero goals across sectors, at multiple levels, and throughout society?

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