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The debate over sustainable development raises the question of regional potential to improve resource management from an ecological point of view. This involves finding substitutes for nonrenewable resources, increasing resource efficiency, and increasing regional autonomy with regard to mass resources. In this context, the question of the possibilities for neighboring highland and lowland regions to find a win–win situation in resource management gains new relevance. Swiss highland and lowland areas served as the study area for the present article. Material flow analysis was applied to quantify the physiological interactions. Energy, human nutrition, and animal fodder served as indicators. Interactions are discussed on the basis of 2 "sustainability scenarios": (1) a 2-kW society, and (2) a diet with low meat consumption. The results led to the following main conclusions. First, physiological net interactions between the regions are currently very low. The natural resource potentials of the regions cannot be used intensively as objects of exchange. Mass resources such as water, biomass, and construction materials play a minor role in the overall regional economic output. With respect to energy and nourishment, the "global hinterland" as the main supplier is much more important for both regions. Second, in sustainability scenarios, the 2 regions could become complementary in the production of food and fodder. In addition, the highlands could eventually become a supplier of renewable energy. Thus, a high degree of sustainability in resource management can increase interregional resource interaction because of the promotion of regional resource idiosyncrasies.

Keywords: *Sustainability in mountainous regions; highland–lowland interactions; material flux analysis; energy; nourishment.*

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Introduction and terminology

Mountainous regions or highlands have been areas of human settlement since the Paleolithic Age. Archeological findings and historical records have provided good documentation of exchanges with the neighboring lowlands over thousands of years (eg, in Osterwalder 1977 for the European Alps). The types of interactions documented encompass a broad variety of services, such as exchange of food and fodder, transport services, health care, and recreation facilities. All these interactions served to overcome regional resource deficits. Every region has to secure its supply of essential resources, such as water, energy, biomass, and construction materials. A region may have the capacity to export some goods, whereas resources may not be adequate to satisfy the regional demand for other goods. For a specific good, the ratio of its regional supply to the overall demand is called the degree of self-sufficiency (DSS). Additional imports have to be paid for either with money earned from exports, from services to other regions, or from subsidies from another region.

From an economic point of view the highlands have generally been the poorer partners. In Europe, alpine societies exported manpower to the lowlands for many centuries. During the last 200 years, tourism and hydropower have become increasingly important as economic resources in highland regions. Despite these newer potentials economic development has been weaker in alpine regions than in the neighboring lowlands. European mountain farmers, in particular, became early recipients of subsidies.

The current debate on sustainable development (since WCED 1987) raises the question of regional potential for improving resource management from an ecological point of view (eg, substituting renewable resources for nonrenewable resources, increasing resource efficiency, increasing the degree of regional autonomy with regard to mass resources). The underlying assumption here is that worldwide population growth and the increased demand for matter and energy per capita will lead to a scarcity of essential goods within the next 2–3 generations. Therefore, each region, on a long-term scale, must develop a strategy to cover its basic demand for resources through a combination of autochthonous and allochthonous sources. The latter must be developed in such a way that "global capital" is not reduced (Daly 1991).

In this context, the question of opportunities for neighboring highland and lowland regions to find a win–win situation in resource management assumes new relevance. The regions compared here are treated as anthropogenic ecosystems. Their material and energy turnovers are encompassed in the notion of "physiological processes." This term is used here in a linguistic sense to mean *physis* (matter and energy) and not in the biological sense of regulation of exchange processes among biological units such as organs and cells. In biology, "metabolic processes," another notion applied to the turnover of matter and energy, is mainly applied to organisms (in other publications it is used synonymously with "physiological processes," eg, Baccini and Brunner 1991). The notion of physiological processes is therefore better suited to describe the exchange of matter and energy in anthropogenic ecosystems. The exchange of matter and energy between regions is referred to as "physiological interaction." The principal question addressed here is: How can physiological interactions be understood and interpreted to shape a long-term strategy in interregional resource management?

Various studies exist on the physiology of lowland and highland regions. The physiology of lowland regions, especially urban regions, is illustrated in Baccini and Brunner (1991), Baccini and Bader (1996), Müller (1998), Redle (1999), and Faist (2000). Dougherty (1994) presented a steady-state analysis for energy, goods, and money for a region in the Atlas mountains (Morocco). Brush (1982) carried out a steady-state energy analysis for a typical family in the Nuñoa district in the Andes, whereas Ralhan et al (1991) did the same for the Pithoragarh district in the central Himalayas. In order to simulate the interactions between population and agricultural production, a dynamic approach was chosen for the Nuñoa district (McRae 1982). All study approaches in mountainous regions focus on the activity of "nourishing," and they examine developing countries as study areas. The models represent solar–agrarian anthropospheres with little industrialization and, therefore, reflect the situation in the European Alps 6–8 generations ago. Their findings are not applicable to mountain regions with tourism, heavy regional and transit traffic, industry, and industrial energy production.

The present study, therefore, describes a methodological contribution for comprehending: (1) the regional anthropogenic physiology of mountain regions on the basis of material flux analysis with a generally applicable system approach, and (2) the interactions between the 2 neighboring regions. The regions discussed here have the following coordinates: 45°49'08" to 47°48'35"N and 5°57'24" to 10°29'36"E.

Methodology

Material flow analysis (MFA) is a method for quantifying regional physiology and physiological interactions (Baccini and Bader 1996). MFA was developed on the basis of field studies to investigate the physiological properties of natural and anthropogenic ecosystems on a regional scale (eg, Brunner et al 1990; Baccini et al 1993; Müller 1998; Redle 1999; Faist 2000). The same method is suitable for studying the material and energy management of companies, industrial plants, and private households. The method consists of 4 steps. In the first step a system is characterized by processes, goods, and indicators (eg, chemical elements, energy, money). In the second step the fluxes and process stocks of the chosen goods and indicator concentrations within the goods are measured. Steps 3 and 4 consist of calculating the indicator stocks and fluxes and interpreting the resulting physiological scheme. The question of resource management under the guidance of "sustainability criteria" is dealt with by using the scenario technique.

The following indicators were chosen for this study:

- Energy.
- Food and fodder, combined in the "activity to nourish" (Baccini and Brunner 1991), subsequently referred to as the activity of nourishing or nourishment.

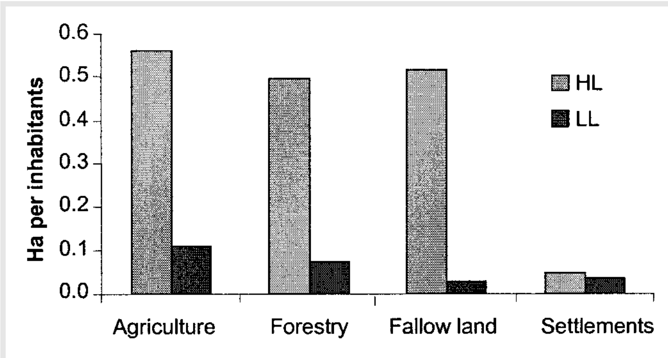
Energy is a key factor in the functioning of large anthropogenic ecosystems. The energy balance illustrates the essential properties of such systems (Redle 1999; Faist 2000). Different energy sources, such as fossil fuels, electricity, firewood, food, and fodder, have to be considered. Water and construction materials are not considered here as essential mass goods because earlier studies have already shown that they are not relevant to interregional exchange in the chosen study area (Baccini 1997).

Study area

A relatively large study area (41,000 km^2) was chosen in Switzerland to investigate interregional relations. Switzerland is a country with a typical highland–lowland neighborhood. About two thirds (28,000 km^2) of the total land area is highlands, and one third is lowlands (13,000 km^2). In this study the concrete borderline between Highland (HL) and Lowland (LL) was chosen on the basis of the Swiss law for subsidizing the highlands (SR 901.1 1997). Data for calculation of the following regional characterizations are taken from the Schweizerische Arbeitsgemeinschaft für Berggebiete (SAB 1997). Only one fourth (1.7 million) of the total population lives in the HL, whereas 5.3 million live in the LL. The population density is, therefore, about 7 times lower in the HL (60 people per km^2) than in the LL (400 people per km^2). The difference in economic potential can be illustrated by the employment situation. The specific employment rate in the HL (0.4 employed persons per capita) is one-third lower than in the LL (0.6 employed persons per capita). Tourism plays an important role in the tertiary sector of the HL. This is indicated by the comparison of the number of tourist overnight stays per inhabitant per year. The HL has 20 tourist overnight stays per inhabitant per year (1997), whereas this figure is 4.5 in the LL.

The theoretical availability of land use types (ie, forestry, agriculture, fallow, settlement), given in hectares per inhabitant, is shown in Figure 1. In the HL the first 3 land use types per inhabitant are higher by a factor of 5–10. With regard to the settlement area (buildings and transport infrastructure), the difference is small. Comparison of the areas for the production of biomass (agriculture and forestry) shows that the HL has a greater production area per inhabitant, although

FIGURE 1 Comparison of land use types (agriculture, forestry, fallow land, settlement) in the Swiss highlands (HL) and lowlands (LL), indicated by hectare per inhabitant (calculations based on data from BfS 1992).



productivity is reduced by the colder climate at higher altitudes. The potential for hydropower is dependent on the precipitation and the usable gravity potential. Because of the larger total area per inhabitant, increasing precipitation with increasing altitude, and higher gravity potentials, the HL also has a greater potential for hydropower.

Systems analysis

The physiological interaction between the 2 regions is made up of 2 MFA subsystems with identical processes and goods (Figure 2). For the 3 indicators chosen (energy, food, and fodder), 7 internal processes are combined with 26 fluxes of goods in each subsystem. Stocks are considered in the processes "forestry," "hydrosphere," and "energy supply." Only 4 types of goods are exchanged between the 2 regions, namely energy, vegetable food, animal food, and fodder. For reasons of comparability, all fluxes are quantified in Watt-hours per year and the stocks in Watt-hours.

To evaluate the physiological status quo and scenarios for the selected indicators, the DSS was calculated as follows:

$$\text{DSS} = \frac{\text{Supply of the region}}{\text{Demand of the region}}$$

The DSS illustrates the regional situation of supply and demand for the investigated goods.

Data sources, assumptions, and calculations

All data were taken from the years 1990 to 1999. Because not all the data needed could be assigned to 1 specific year, the results reflect an average situation for the 1990s. Basic data for the 2 regions were taken from the following sources: demographic data from SAB (1997) and BfS (1999), area statistics from BfS (1992) and SAB (1997), tourist overnights from BfS (1997a), SAB (1997), and AWG (1998), and employment data from SAB (1997), AWG (1998), and BfS (1999). The energy supply and consumption situation of Switzerland is reflected in SEV/VSE (1996). Additional data for traffic came from CIPRA-International (1994), BfS (1997b), and Meier (2000). The energy consumption for tourism consists of tourist traffic and average energy consumption per tourist-overnight multiplied by the number of overnight stays. Wick (1983) and Meier and Wick (1988) showed that there is no significant difference in the energy demand of households at different sites in Switzerland. Therefore, household energy consumption was calculated using the Swiss average data multiplied by the regional number of inhabitants. Energy consumption for trade, services, and industry was calculated using the average energy consumption per employee for each sector multiplied by employment in the 2 regions.

For detailed insight into food and fodder fluxes, it is necessary to aggregate agricultural production to vegetable food, animal food (food for humans based on animal products, such as meat, dairy products, eggs), and fodder (animal feed, such as grass, corn, grain). The sources for this aggregation were SBV (1994), BfS (1995), LBL (1997), and BfS (1999). Vegetable food and fodder production was calculated using cultivation areas per agricultural species and average yields. The most important assumptions for calculations in this system are as follows:

- Food consumption in nutritive value per inhabitant and household energy consumption are similar in both regions.
- Energy consumption per place of employment in the same economic sector is the same for both regions.
- All different energy sources can be substituted.
- Energy consumption for tourism was only calculated for consumption in the system. Energy turnovers for traveling to and from the system are not included.

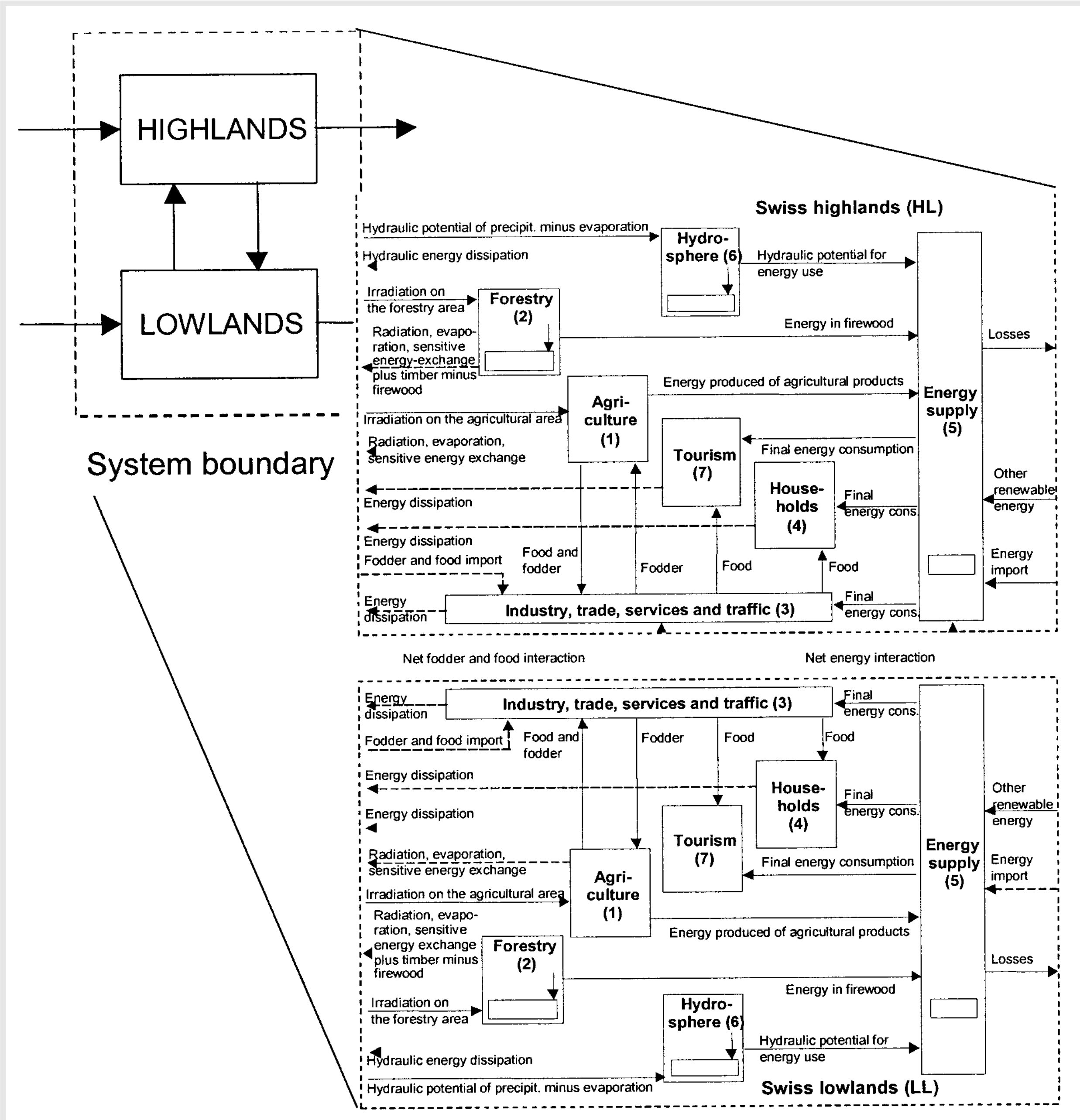
The dashed fluxes in Figure 2 were calculated from the mass balance equations in the corresponding processes.

The statistical sources do not give error estimations. Some important parameters, such as area, population, employment, animal stocks, and tourist overnight stays, are assumed to have small error ranges (<5%). The errors for other data are estimated to be 20% at the maximum. Error propagation for the resulting fluxes (dashed lines in Figure 2) was calculated to be between 14% and 48%.

Scenarios

The boundary conditions that follow will shape future development. Measures to increase hydropower production are limited to 10% at the most, primarily for hydrological reasons and secondarily for ecological

FIGURE 2 Systems analysis based on MFA with a 2-region highland–lowland system for energy and food/fodder.



reasons (protection of mountainous aquatic ecosystems). From a qualitative point of view, tourism seems to have reached the upper limit (Krippendorf and Müller 1986). Also, animal production has reached its limits in ecological terms. Therefore, in a trend scenario the economic disparity can be overcome only by consequent adaptation of the highland economy to the economy of its lowland partner. However, in "sustainable development scenarios," the resource groups, (1) energy, and (2) food and fodder, have to meet other boundary conditions. A constant population is assumed for both scenarios.

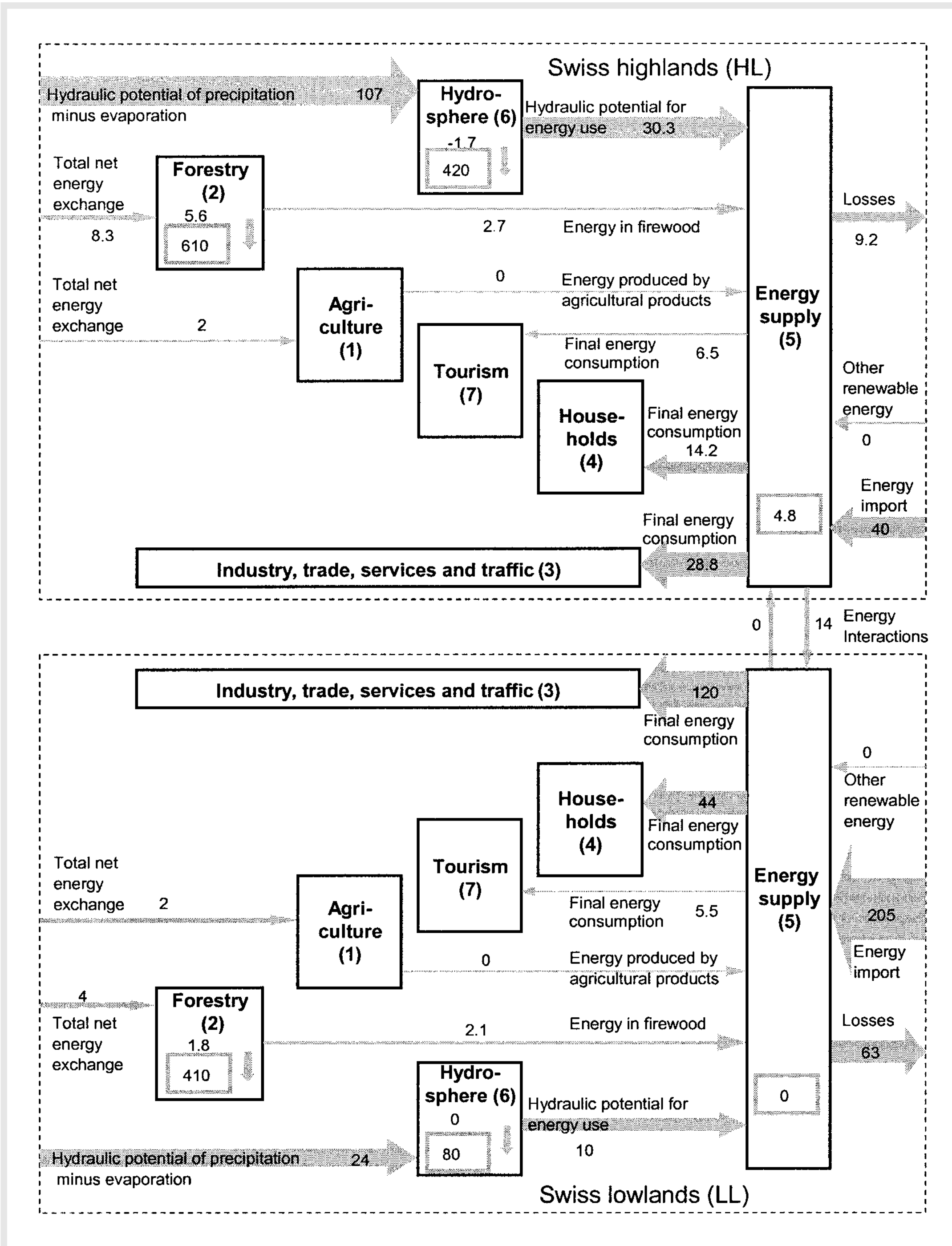
Energy

In Switzerland the primary energy power supplied per capita currently amounts to 6 kW. A global threshold value of 2 kW per capita is postulated. A drastic reduction in the overall demand for energy by a factor of 3 is under discussion as a long-term regional limit for urban systems such as the Swiss lowlands (Imboden and Baccini 1996).

Nourishing

For the activity of nourishing, a sustainable development scenario sets goals to reduce meat consumption

FIGURE 3 Energy fluxes and stocks for the Swiss highlands (HL) and lowlands (LL) in the 1990s (fluxes in TWh/y, stocks in TWh).



and replace it with more vegetables. This is the result of a stepwise cultural change in society for a combination of ecological, sanitary, and ethical reasons. The following assumptions were chosen for this scenario:

- Meat consumption is reduced by 50% from its present level in both regions (from 56 to 28 kg/inhabitant/y).
- The area under agriculture remains constant in both regions.
- Animal production in the HL is kept at the present level because climate effects hinder the efficient replacement of pastures for coarse fodder production by vegetable food production.
- In the LL, agriculture with vegetable food produc-

tion will replace pastures. No significant animal husbandry will take place in the LL.

- In the HL the area used for the production of concentrated fodder will be used for the production of vegetable food, whereas production of concentrated fodder remains constant in the LL.

Results

Energy balance

Figure 3 shows the energy fluxes and stocks for the 2 regions in the 1990s. The energy consumed is transferred entirely into heat. In order to simplify the graphic, these dissipation fluxes are not shown. Because of the large differences in area and population between the 2 regions, standardization per area and inhabitant are not useful for comparisons. As a consequence, the figure contains absolute results per region. Agriculture (1), Forestry (2), and Hydrosphere (6) are the energy-supplying processes, whereas Industry, Trade, Services, and Traffic (3), Households (4), and Tourism (7) are the energy-consuming processes. Both regions have to import energy (mainly fossil fuels) to run their systems. The HL produces end-energy of about 28 TWh/y (of which 80% is hydroelectric power) and theoretically covers about one half of its total demand (about 54 TWh/y; see also Table 1). The corresponding DSS amounts to only 6% in the LL. The net transfer of hydroelectric power and firewood (both renewable) of around 14 TWh/y from the HL to the LL is more than compensated by the 40 TWh/y of fossil fuel that is imported into the HL from the "global hinterland" (Figure 3).

As expected from the general pattern of economic activities (see "Study area"), the LL tends to consume slightly more energy (32 MWh/person/y) than does the HL (29 MWh/person/y). This is mainly because of the process Industry, Trade, Services, and Traffic (HL: 17 MWh/person/y, LL: 23 MWh/person/y) On the contrary, Tourism is higher in the HL (HL: 3.8 MWh/person/y, LL: 1.0 MWh/person/y). Households, the second-place energy consumers, do not differ between the HL and the LL as a consequence of the assumptions (8.2 MWh/person/y for both regions).

Food and fodder (the activity of nourishing)

Animal food and fodder are combined in 1 system (Figure 4). The inputs of solar energy are not shown here. Therefore, the processes grouped under Agriculture serve as energy sources. Each regional system is divided into 2 coupled subsystems, namely, the Fodder System and the Animal Food System. The first 2 subsystems (left) concentrate on animal production and input goods. The target products of animal production—the animal food—are exported to the Animal Food System

TABLE 1 Comparison of regional energy supply and consumption, and the degree of energy self-sufficiency (DSS, in TWh/y) for the status quo and a 2-kW scenario, indicated for the Swiss highlands (HL), the Swiss lowlands (LL), and Switzerland as a whole (CH).

	HL	LL	CH
Total energy supply for the status quo and for a 2-kW scenario (TWh/y)	28	11	39
Total energy consumption for the status quo (TWh/y)	54	182	236
Total energy consumption for a 2-kW scenario (TWh/y)	28	93	120
DSS for the status quo (%)	53	6	16
DSS for the 2-kW scenario (%)	102	11	32

FIGURE 4 Animal food and fodder fluxes in GWh per region and year for the Swiss highlands (HL) and lowlands (LL) in the 1990s.

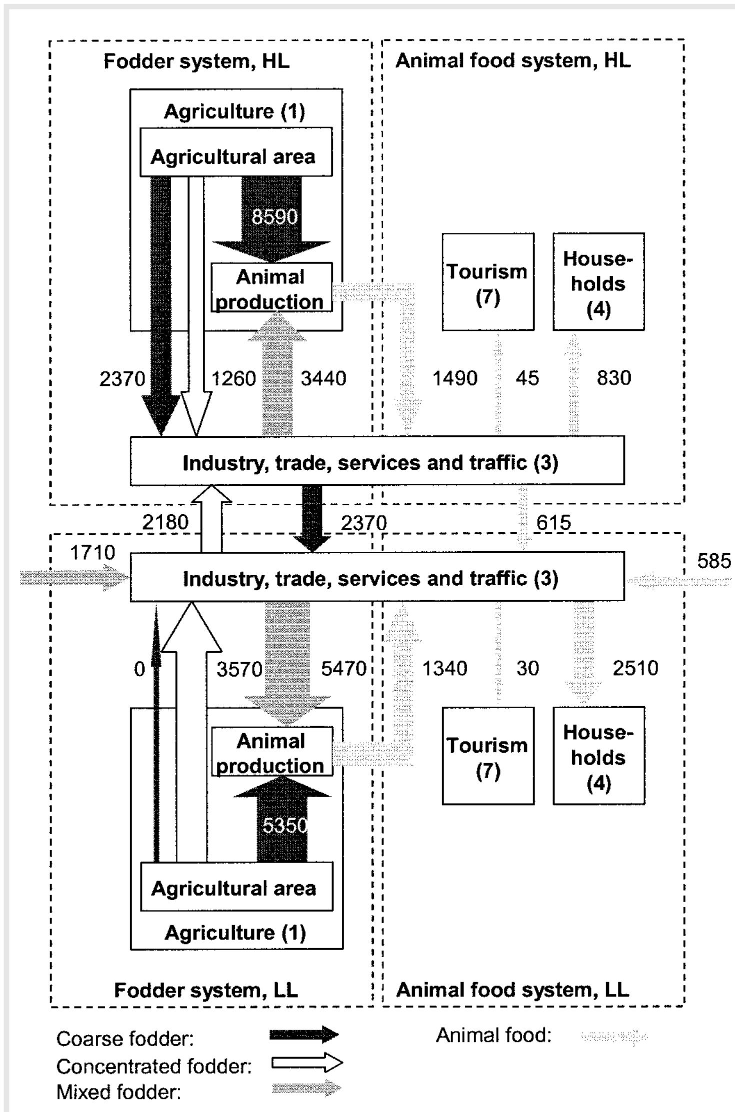


FIGURE 5 Vegetable food fluxes in GWh per region and year for the Swiss highlands (HL) and lowlands (LL) in the 1990s.

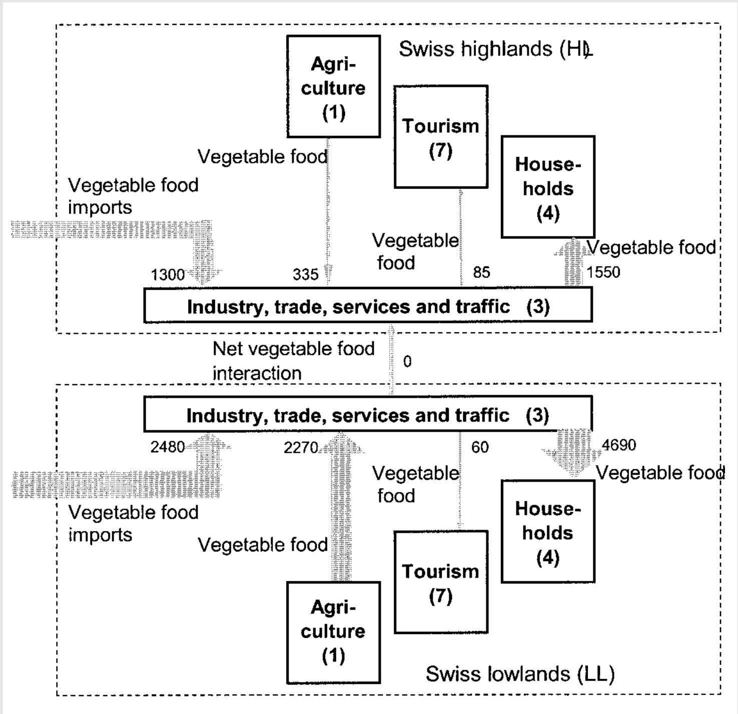
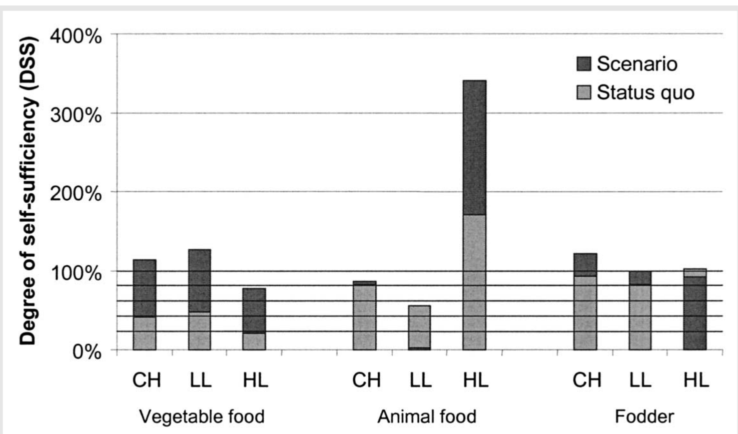


FIGURE 6 DSS for the status quo and scenario for the activity of nourishing, indicated for vegetable food, animal food, and fodder for Switzerland (CH), the Swiss lowlands (LL), and the Swiss highlands (HL).



subsystems. The HL is a net exporter of coarse fodder to the LL but a net importer of concentrated fodder from the LL. In energy units, the net energy flux in fodder exchange between the HL and the LL is very small (approximately 200 GWh/y).

There is a net export of animal food from the HL to the LL (meat and dairy products). This contribution is a significant portion of the total animal food consumption in the LL (approximately one fourth). This indicates that an old tradition in the alpine economy is still practiced at present. Over the centuries, cheese and meat of alpine origin have been famous export products throughout Europe (Bätzing 1984).

The vegetable food exchange is given in Figure 5. Here too, the inputs from solar energy are not shown. Vegetable food comprises all agricultural products not refined by animal husbandry, such as cereals (including all farinaceous products, such as bread, pasta), vegetables, and fruit. It can be concluded that the net interregional interactions are practically zero. Both regions are highly dependent on imports from other regions. For climatic reasons, imports are more relevant in the HL. As already noted for animal food consumption (Figure 4), the Tourism process is not a major consumer of food.

Results of the scenarios

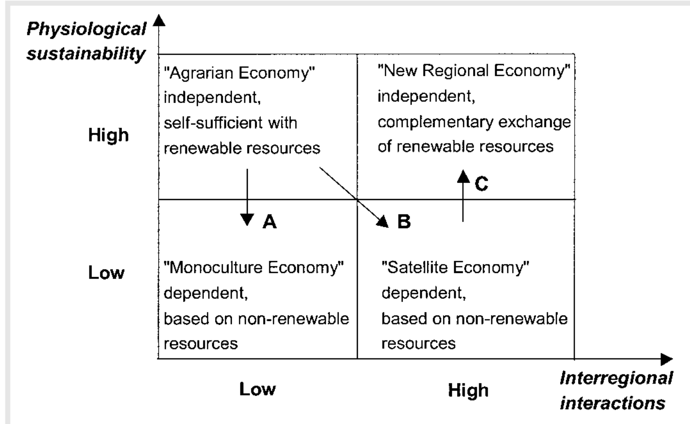
1. The results of a 2-kW scenario are presented in Table 1. The following consequences can be postulated for the physiological situation of the 2 regions. The HL becomes self-sufficient in energy (at present only 53%) and develops into a net exporter of energy to a very modest extent, assuming hydropower and fuel wood production stay at their present levels. The LL would not benefit in a similar way. Despite the same reduction in overall energy demand, the contribution from the total HL export would not exceed 1% of the LL demand.
2. The consequences of a scenario with a diet of low meat consumption are given in Figure 6. The HL becomes the most important supplier of meat for the LL (approx. 80% of the LL demand). With regard to vegetable food production the overall substitution of increased lowland production for imports amounts to 120%.

Discussion and conclusions

With regard to physiological demands, the lifestyle in the alpine HL no longer differs from the urban lifestyle of the neighboring LL. The majority of the highland population lives an urban life at a higher altitude. The following arguments support this statement:

- The settlement area per inhabitant is the same in both regions (Figure 1).
- Studies on a communal level show that today 60% of the population in the HL lives in urban or periurban municipalities (Perlik 1999).
- The studies by Wick (1983) and Meier and Wick (1988) already mentioned calculated household energy consumption and showed that it does not differ for different locations in the study area.
- The mean regional daily transportation distance covered per inhabitant is almost the same in both regions. The spatial modal split in the different

FIGURE 7 Types of regional economies in terms of characteristics of physiological sustainability (indicated by the DSS based on renewable resources) and interregional interactions (indicated by exchange of goods). Historically, mountainous regions have been transformed from agrarian economies along paths A and B. The next transformation would be along path C.



kinds of mobility does not show significant differences for the 2 regions chosen (BfS 1997b). Thus, energy consumption for transportation can be assumed to be similar in both regions.

The regional physiological potentials are different. They are higher in the HL (higher arable land for biomass production per inhabitant, as shown in Figure 1, and higher hydraulic energy potential, as shown in Figure 3). Nevertheless, the consequences of the present supply–demand situation are the same for both regions. With respect to energy and nourishment the global hinterland is the main supplier for both regions and is more important than trade between the regions. With regard to the chosen indicators the net interactions between the regions are very low. In addition, the higher physiological potential of the HL is not important in terms of interactions with the LL. The reasons for these low interactions can be partly found in the socioeconomic situation. Energy costs and the costs of nourishment form a minor part of the overall private household budget. For the average Swiss household (BfS 1999), expenditure is approximately 5% for energy (in housing and transport), and for nourishment it is roughly 10%. It must be noted that these 2 items show a relative decrease from 1975 to 1992. Because of the minor importance of these budget items and the low prices in the world market for the goods studied, there have been no economic incentives to invest in a more intensive interregional resource exchange during the last 3 decades. In the present situation any of the regions studied can earn money from regional potentials through exports (in the final analysis) to pay for other essential imports. The LL can solve this problem with its competence in the secondary and especially the tertiary economic sectors in the global market. The LL's employment density (employees per inhabitant; see "Study area") is one-third higher and has a much higher percentage in the tertiary sector (HL: 0.2 employed persons per capita, LL: 0.4 employed persons per capita). As an economically weaker region, the HL is less competitive in the global market (Muggli 1984) and, therefore, has fewer chances to earn money outside the region. The resulting disparities are greatly reduced by subsidies from the LL to the HL, which are based on national policy.

The 2-kW scenario shows the possibilities of regional energy potentials, given a substantial reduction in energy consumption. Such a reduction, without severe damage to the quality of life, is only possible if a total reconstruction of the transportation, communication, and building infrastructure can be realized within the next 2–3 generations (Imboden and Baccini 1996; Baccini and Oswald 1998; Redle 1999). Whereas the HL becomes self-sufficient in energy in a 2-kW scenario, the LL has to enlarge its autochthonous renewable energy production in a significant way in order to substantially increase its DSS (Table 1). In this scenario the interregional interactions stay at a low level, but the resource deficits decrease in both regions.

The nourishing scenario shows a possible win–win situation in resource management in the 2 regions. With a change in diet the 2 regions could become complementary in nourishment production and self-sufficient as a regional neighborhood (Figure 6). The discussion of the "sustainability scenarios" is based on different types of regional economies, as presented in Figure 7. Historical agrarian societies (before industrialization) were sustainable in the physiological sense because their regions could survive without much economic interaction. Economically monocultural regions (eg, coal exploitation, steel production, or branches in the tertiary sector such as the tourist industry) have a low diversity of goods exchange and depend mostly on imported essential mass resources (eg, energy). Satellite economies depend strongly on special political or financial support (or both) from relatively strong centers (eg, Hong Kong during the British Empire, Swiss lowland support for the highlands). In historical terms, mountainous regions were transformed from "agrarian economies" on paths A or B. The present study shows that the status quo of the HL is characterized as a mixture of "monocultural" and "satellite economies." Both regions (HL and LL) are strongly dependent on the hinterland with regard to the chosen indicators (energy and food). They are mainly based on non-renewable energy sources. Applying the 2-kW scenario, the HL could become an independent agrarian economy, whereas the LL would remain a hinterland-dependent economy in terms of energy. Because of their complementary economies, in the nourishing scenario the 2 systems can form a hinterland-independent system for food and fodder (called "new regional economy" in Figure 7). In combination with the 2-kW scenario, the HL could move along path C.

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