

Food security in high mountains of Central Asia: A broader perspective

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Abstract

Addressing food security in high mountains is a multidimensional conundrum because of complex climate patterns and environmental attributes. These conditions affect water supplies, biodiversity, droughts, and other hazards. The climate change–land degradation nexus, although it is difficult to disentangle, poses formidable challenges. Isolated mountain villages, coupled with poverty, a strained subsistence existence, conflict, and marginal lands make the residents vulnerable to malnutrition, stunting, and food access. Because the arable land is mostly in confined valleys, food production is insufficient. The soils are typically infertile, with little organic matter; on hillslopes, thin soil and rock cover, coupled with short growing seasons, restrict crop production. High-elevation pastures are overgrazed, and the natural hazard impacts on food security are often overlooked. We examine food security through these multifaceted stressors, instead of merely focusing on production and distribution, and present an integrated approach to assess natural and anthropogenic stressors and feedback loops affecting food security linked to planning, mitigation, and coping strategies.

Keywords: climate change, native vegetation, land degradation, water sources and management, Pamir

Mountainous terrain represents 27% of the Earth's land surface and supports 15% of its people, many of whom are impoverished and suffer from food insecurity (Romeo et al. 2020). Food security has been defined in different ways, but at its core, means that people have access to sufficient, safe, and nutritious food at all times to support healthy livelihoods (Gross et al. 2000). Mountain people are highly vulnerable to food insecurity because of poor land productivity, increasing production and transportation costs, severe and changing climate, social instability, formidable terrain, poor market access, and natural hazards (Hussain et al. 2016, Klein et al. 2019, Caiserman et al. 2022). The effects of many such stressors have not been collectively examined relative to alleviating food insecurity in mountain regions, and recent external pressures exacerbate these problems.

Despite the many ecosystem services (e.g., clean water, biodiversity) provided by mountains of developing nations, most mountain people live in poverty, partly because of the harsh environments, a dependence on external supplies, socioeconomic instability, and exploitation of natural resources (e.g., fuelwood collection); (Uhlir and Kreutzmann 1995, Kreutzmann 2001, Mishra 2002). Therefore, food security is a major problem facing the residents, many of whom rely on subsistence agriculture and livestock husbandry (Kreutzmann 2003, Shaumarov et al. 2012). Of the more global solutions to achieve food security—e.g., reducing food waste, overconsumption of food, and expanding land resources and aquaculture (Cole et al. 2018)—few are relevant to high mountains.

The remote mountain villages in Central Asia have always existed on the cusp of poverty because of the formidable terrain and the lack of diverse and nutritional crops, but conditions have worsened with the ongoing economic instability following the

Soviet collapse in early 1990s (Babu and Rhoe 2006). When state farms were dissolved in the post-Soviet era, socially subsidized agricultural operations disappeared, and many farmers reverted to subsistence agriculture, including household kitchen gardens (Breu and Humi 2003, Shaumarov et al. 2012). This situation is compounded by widespread outmigration of rural labor, largely to Russia, leaving women in charge of family farms and subsistence activities (Laruelle 2007). In addition, the COVID-19 pandemic, currency devaluation, and a reduction in wheat export caused by the Ukraine war have contributed to this instability (Shimizutani and Yamada 2021, FAO 2022). Although we address these socioeconomic externalities and feedback loops, we focus more on the biogeophysical stressors that are unique to high mountain environments.

Soil and water constraints in these high mountains create challenges for food security. Arable soils are sparse and are confined largely to valley bottoms, and soil degradation from overgrazing increases erosion and the loss of soil carbon and nutrients (Lal 2010, Sidle et al. 2019, Hossain et al. 2020). Water is critical to food production; runoff is supplied to the valleys by a combination of seasonal snowmelt, glacial melt, and permafrost thaw, together with periodic rainfall (Armstrong et al. 2019, Nie et al. 2021).

The ubiquitous incised valleys and steep slopes leave mountain agriculture exposed to direct impacts of multiple natural hazards, including landslides, debris flows, floods, rockfall, and snow avalanches (Sidle 2020, Nie et al. 2021, Caiserman et al. 2022). Steep terrain limits radiation, especially on their shaded aspects, exacerbating already short growing seasons. Mountain topography induces local effects on precipitation and temperature regimes, as well as unique climate change impacts, including interannual variability in snow and drought cycles (Dietz et al. 2013,

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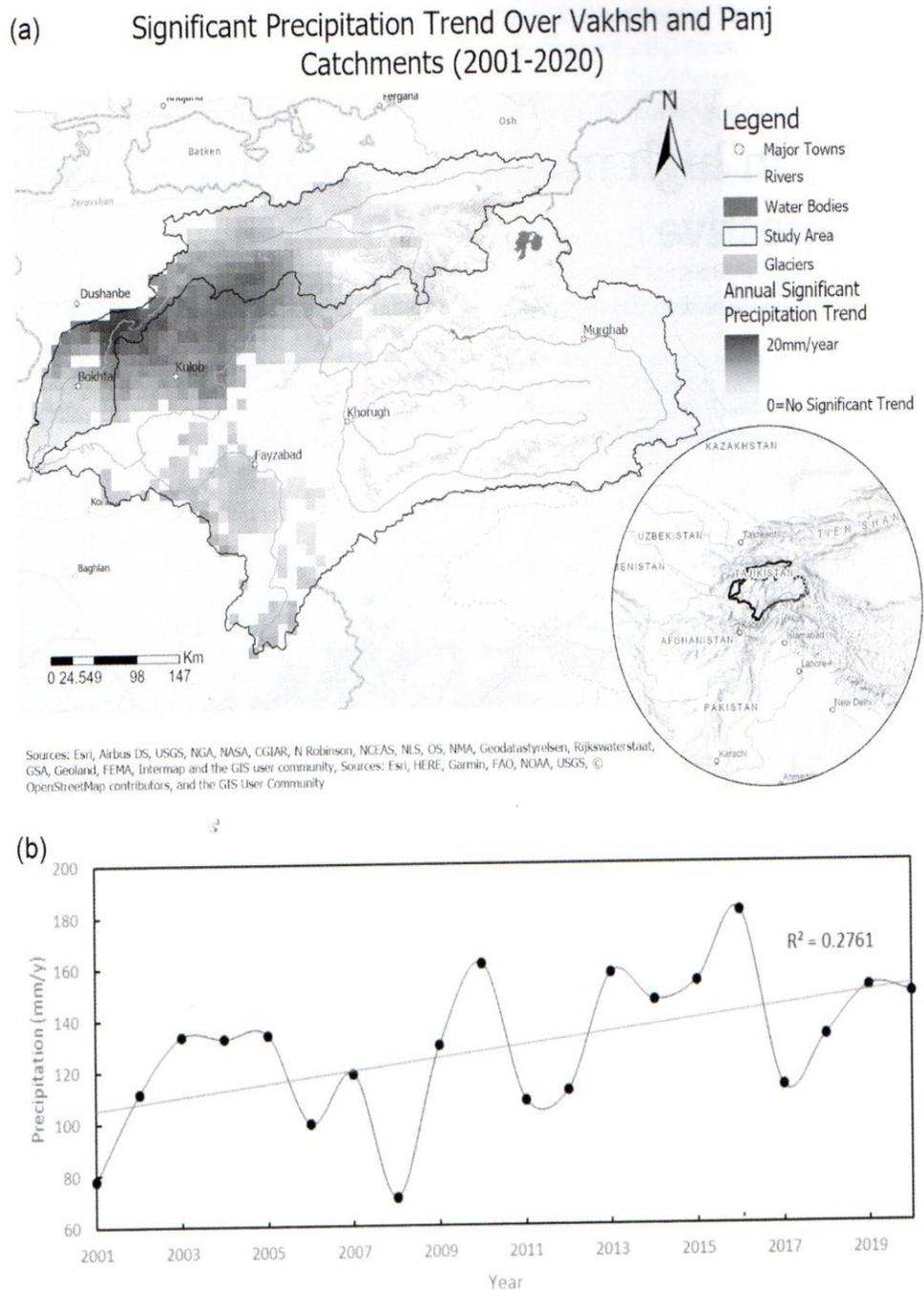


Figure 1. (a) Annual trends in total precipitation from 2001 to 2020 across the Panj and Vakhsh River basins (Tajikistan and northern Afghanistan); the colored pixels show significant changes. (b) Positive trend in average annual precipitation across the two basins. All precipitation values are based on IMERG remotely sensed data.

Guo et al. 2018). Many areas of the Pamir and the Hindu Kush have experienced recent long-term droughts, causing low crop yields, likely indicative of climate trajectories (Rousta et al. 2020, Hussaini et al. 2021). These environmental shocks and uncertainties, together with the isolation of mountain villages and their inherent social stresses, create food insecurity in mountain regions because of periodically failed or reduced crops, restricted access, and uncertain water supplies.

In the present article, we assess food security from multiple perspectives. We draw on our knowledge from Central Asia, particularly the Pamir, in Tajikistan, to illustrate how different factors uniquely affect food security, and we discuss their interactions, some challenges, and sustainable trajectories for improving the food security of poor mountain dwellers.

Climate patterns and constraints

Although climate change has been broadly implicated in food security challenges across the Pamir (e.g., Kassam 2009, Hussaini et al. 2021), climate patterns are far from consistent. Precipitation in the region is characterized by spatial and interannual variability rather than consistent trends (figure 1a, 1b), which do not follow the model of increasing precipitation with elevation. Spatial temperature trends exhibit a clearer pattern than precipitation, decreasing with elevation. Above approximately 2000 meters (m) above sea level, the average annual temperature is below 0 degrees Celsius, which highlights the severe climate of the Pamir. Although the temperatures in most areas are increasing, the trends vary widely across the region (Finaev et al. 2016, Haag et al. 2021). There is little warming below 2000 m in western Tajikistan, where the large-scale agricultural lands exist. The overall variations in

temperature and precipitation are not surprising, given the complex orography, which affects atmospheric processes and the local climate (e.g., Curio and Scherer 2016). Many climate-trend studies in the Pamir have yielded variable and contradictory results (Mirzokhonova et al. 2018), making assessments of climate change on food security uncertain.

Constraints on the climate

The glaciers of the Pamir are protected by southern mountains that block air masses, shielding them from climate change impacts (i.e., the Pamir–Karakoram Anomaly; Forsythe et al. 2017, Barandun et al. 2020). However, this air blockage reduces precipitation in the Eastern Pamir, where annual precipitation is as low as 50 millimeters, making cultivated agriculture mostly impossible. Many glaciated regions of the Pamir have experienced little change in ice mass, particularly where precipitation has increased.

Rainfall, snow, and temperature, including temporal regimes, are important climate controls on vegetation growth and food security. Because of orographic influences and local atmospheric circulation, some areas receive more precipitation, and others receive less, with a tendency to shift from less snowfall to more rain in some areas (Li et al. 2020). Precipitation across the Panj and Vakhsh River basins is highly variable but significantly increased from 2000 to 2020 (figure 1b), with the largest increases at the lower elevations of western Tajikistan (figure 1a), particularly in late spring. Increases in spring rainfall bode well for agriculture at lower elevations, but higher temperatures in Central Pamir and on the high plateaus of Eastern Pamir and the Wakhan Corridor will reduce grazing capacity and further limit food production if the trends persist.

Aspect is important in this dissected mountain topography; the shaded, north-facing slopes are exposed to less sunlight, promoting higher soil moisture and more lush, green vegetation than the south-facing slopes (Abalori et al. 2022). Such effects also extend into shaded, dissected valleys, where the period of snowmelt may extend and where evapotranspiration is less during late summer months (Hrach et al. 2021).

Climate and food security

Given the complex dynamics and spatially variable climate in the Pamir, the current and future effects on food security are highly variable, and there is no one-size-fits-all strategy for adaptation. Warming may support mountain farmers in parts of the Pamir, facilitating cultivation and food production in midelevation terrain, provided soil moisture, nutrients, and irrigation water are ensured. However, variation in the frequency and severity of droughts, untimely rains, and hazards pose challenges for mountain farmers and pastoralists and threaten food security (Chapagain and Raizada 2017). Drought affects pastures, reducing the amount of quality forage available to livestock. In the dry, Eastern Pamir and Wakhan Corridor, already degraded pastures will likely experience further stress because of warmer summers and increased grazing pressures, negatively affecting already tenuous food security. Large diurnal temperature fluctuations, typical of drylands, exacerbate the limited growing seasons. In contrast, the lower foothills in western Tajikistan have not experienced significant warming, and precipitation increased in some areas, likely benefiting agriculture, with the exception of untimely floods.

Further climate warming may increase the prevalence of new insects, pests, or pathogens (Dale et al. 2001) damaging economi-

cally important crops as was noted by farmers in Afghanistan and Tajik Badakhshan. Throughout the region, both spatial and temporal variability of precipitation (figure 1), particularly snowfall, are major challenges for food security, begging the need for local prediction of the amounts and timing of snowmelt (Beniston et al. 1997, Zhumanova et al. 2021).

Agrobiology and biodiversity

About 73% of Tajikistan's population resides in rural areas and relies largely on subsistence agriculture as its economic mainstay. The increasing population coupled with climate change threatens the food security of Pamir residents, where the average household agriculture landholding (less than 0.2 ha) is insufficient to supply family food (Kreutzmann 2003). Mountainous terrain constricts agricultural development, with only 0.4% of the land considered arable (Stucker 2009). The residents practice so-called combined mountain agriculture, growing food and fodder in small plots near their homes and grazing livestock in nearby pastures. The production does not meet the demand; therefore, more expensive food imports are essential to meet the people's needs. A comprehensive, albeit dated, breakdown of rural household income distribution in the mountainous Gorno-Badakhshan Autonomous Oblast (GBO) is as follows: livestock earnings, 36%; farming, 33%; salaries, 14%; pensions and benefits, 6%; remittances 4%; and business, trading, casual labor, and other sources, 7%; lower elevations of the Rasht valley and the Eastern Khatlon Oblast had similar income distributions in the agriculture sector, with more emphasis on livestock in Rasht (Robinson and Guenther 2007).

Biodiversity: Native vegetation and crops

Various native crops and plants are grown throughout the Pamir (table 1). These plants, locally used for making curries, soups, teas, jams, pickles, juices, compotes, and medicines, typically grow at elevations between approximately 1500 and 3000 m above sea level (Khan et al. 2022). The strong dependency of Pamir communities on native species for food security and herbal remedies underlines the importance of assessing the impacts of climate change and land degradation and implementing restoration strategies.

The number and range of species, which define biodiversity, will likely decline as temperatures rise (Nowak et al. 2020). Warming, coupled with increasing atmospheric carbon dioxide, affects photosynthesis, resulting in increased water-use efficiency by plants, enhanced photosynthetic capacity, and increased growth, which may lead to dense vegetation with closed canopies. This, in turn, creates high competition among species for water, nutrients, and sunlight and ultimately affects plant community structure and function (table 2).

The mating systems of plants, along with anthropogenic disturbances (e.g., fragmentation, climate change), affect genetic diversity (Eckert et al. 2009, Guan et al. 2021). Inbreeding reduces genetic diversity, whereas outbreeding increases diversity. Genetic drifts can occur in rare and fragmented plant populations, leading to a loss of alleles, reducing genetic diversity (Honnay and Jacquemyn 2007). Although longer growing seasons and higher carbon dioxide levels in a warming climate may benefit some species, the rising temperatures can promote invasive plants, insects, and pests (table 2); however, high elevations appear less prone to these impacts (Alexander et al. 2016). Although several studies have reported positive effects of climate change (increased

Table 1. Native crops and plants used for consumption and sale in the Pamir.

Scientific name	Common name	Uses in the Pamir
<i>Rosa canina</i> L.	Dog rose ^a	Herbal teas
<i>Glycyrrhiza glabra</i> L.	Licorice root	
<i>Matricaria chamomilla</i> L.	Chamomile ^b	
<i>Ribes nigrum</i> L.	Black currant ^a	
<i>Barberis vulgaris</i> L.	Barberry ^a	Vegetables for cooking and curries
<i>Coriandrum sativum</i> L.	Coriander ^b	
<i>Carthamus tinctorius</i> L.	Saw flower ^b	
<i>Solanum melongena</i> L.	Eggplant	
<i>Fagopyrum esculentum</i> Moench	Buckwheat	
<i>Linum usitatissimum</i> L.	Flax/lint	
<i>Juglan regia</i> L.	Walnut ^a	
<i>Prunus armeniaca</i> L.	Apricot	
<i>Morus alba</i> L.	Mulberry ^a	
<i>Prunus avium</i> L.	Wild cherry ^a	
<i>Ficus carica</i> L.	Figure ^a	Preparing jams and pickles
<i>Prunus amygdalus</i> Batsch.	Almond ^a	
<i>Hippophae rhamnoides</i> L.	Seabuckthorn ^a	
<i>Rubus crataegifolius</i> Bunge.	Raspberry	
<i>Prunus malus</i> L.	Apple	
<i>Prunus armeniaca</i> L.	Apricot ^a	
<i>Prunus persica</i> L.	Peach	
<i>Ferula assafoetida</i> L.	Stinking gum ^a	
<i>Prunus domestica</i> L.	Plum	
<i>Pyrus persica</i> Pers.	Pear	
<i>Punica granatum</i> L.	Pomegranate ^a	Juices and compotes
<i>Cerasus avium</i> L.	Sweet cherry	
<i>Crataegus sanguinea</i> Pall.	Hawthorn	
<i>Rubus crataegifolius</i> Bunge.	Raspberry	
<i>Pyrus malus</i> L.	Apple	
<i>Ribes nigrum</i> L.	Black currant	
<i>Ferula assafoetida</i> L.	Stinking gum	
<i>Hippophae rhamnoides</i> L.	Seabuckthorn	
<i>Prunus armeniaca</i> L.	Apricot	
<i>Morus alba</i> L.	Mulberry	
<i>Prunus domestica</i> L.	Plum	Spices and condiments
<i>Coriandrum sativum</i> L.	Coriander ^b	
<i>Bunium persicum</i> Boiss.	Black cumin ^b	
<i>Allium stipitatum</i> Regel.	Wild onion	
<i>Mentha asiatica</i> Boriss.	Mint ⁺	Soup making
<i>Capparis spinosa</i> Wild.	Caper	
<i>Vicia faba</i> L.	Horse bean	
<i>Phaseolus vulgaris</i> L.	Red bean	

^aMedicinal uses of fruit, gum, nuts, and roots.

^bMedicinal uses of flowers, leaves, and seeds of plants. Source: Based on data from Khan and colleagues (2022).

temperatures and precipitation) on wheat production in the region, progressive warming can induce soil salinity and flowering sterility (Sommer et al. 2013). Pulses, major sources of protein in poor mountains, have recently suffered from droughts, requiring careful varietal selection (Hussaini et al. 2021).

Native vegetation is foundational to ecosystem processes and supports larger insect populations than nonnative species do (Tallamy and Shiver 2021). Many native species can enhance food security in the Pamir; however, some may be threatened by climate change (tables 1 and 2; Khan et al. 2022). Given climate change projections, the distribution range and abundance of widespread and narrow-range endemic species may decline (Lima et al. 2022).

Biodiversity supports ecosystem function, productivity, and services where all species play important roles (Balvanera et al. 2006). Native crops such as coriander, beets, safflower, horse bean, and brown lentil, as well as indigenous plants, are not only used

for herbal remedies and food but also collected and sold in local and national markets. The major edible and medicinal indigenous species traded in markets include licorice root, black currant, golden root, stinking gum, black cumin, St. John's wort, mint, rosehips, chamomile, and barberry (Khan et al. 2022). In addition to the dietary benefits associated with highly diverse plants, they provide options for supplementing local incomes (Jones 2017).

Adaptation strategies

Agricultural crops in different regions are typically sensitive to climate change (Howden et al. 2007). Plants adapt to environmental stress by altering their metabolism, flowering, growth, and reproduction and by migrating toward more favorable climates (e.g., Raza et al. 2019, Choudhary et al. 2021). It is difficult to predict the impact of climate change on individual

Table 2. Comparative analysis of climate change effects on native plants and agriculture crops.

Climate changes	Native plants	Agriculture crops
Longer growing season	<p>Earlier spring and later autumn seasons.</p> <p>Native plants derive more benefits and may flourish because of adaptive capacity</p> <p>Longer seasons cause early emergence of insects and pests altering life cycles or increasing pests</p> <p>Invasive and undesirable plants that thrive in warmer climates may shift to higher latitudes</p>	<p>Farmers can cope by diversifying crops or using multiple harvests</p> <p>Productivity may increase and afford new planting opportunities</p> <p>Limitations on the types of crops grown</p> <p>Encourages growth of invasive species and increases irrigation demands</p> <p>Ecosystem structure may be disrupted</p> <p>Certain crops may suffer because of longer growing seasons</p>
Rising temperature	<p>Climate warming affects native plants</p> <p>Native plants experience more heat stress, causing higher water demands</p> <p>Invasive species and pests may affect biodiversity and cause native species loss</p> <p>Increases in heat waves cause stress in plants and lower productivity</p> <p>Soil water becomes less available making it difficult for some plants to thrive</p>	<p>Reduced agricultural productivity.</p> <p>More frequent droughts, wildfires, and pest outbreaks cause the loss of plant species</p> <p>Crop habitats and planting dates may shift</p> <p>Droughts hinder farm practices and reduce productivity</p> <p>Recently rising temperatures affected farmers in southwest Tajikistan, where tomato plants are drying before ripening</p>
Adaptation measures	<p>Native plants adapt to local climate and soils where they naturally occur</p> <p>Once established, native plants need little management and maintenance</p> <p>Many native plants have flowers and produce abundant fruits and seeds</p> <p>Native plants require less water than crops</p> <p>They provide vital habitat for birds and other wildlife</p>	<p>Improved resilience by diversifying crops and via new genetic technologies.</p> <p>Integrated crop management, species selection associated climate change</p> <p>Agroforestry species selected so plants do not compete but collaborate.</p> <p>Diversity of crops and trees allows sites to be productive year-round</p> <p>Changes in farm schedules are needed</p> <p>Promote healthy diets, reduce food waste</p>

species, which have different capacities to adapt or migrate. Common farm adaptation strategies are the introduction of drought-resistant crop varieties, crop diversification, changes in cropping patterns and planting schedules, conserving soil moisture using limited tillage and mulching, improving irrigation efficiency, and afforestation and agroforestry (Akinngbe and Irohbe 2014, Altieri et al. 2015).

Planting adapted vegetation is recommended as a key practice to conserve soil and water (Shea 2014). An ongoing study in the Pamir on varietal screening of wheat indicates that two indigenous varieties, *Surkhak e Ishkashimi* and *Safedak e Ishkashimi*, outperformed exotic varieties of winter and spring wheat from China and Pakistan. Adapted crops reduce the negative impacts of climate change and promote more stable production. Introducing new crops or reinstating heritage crops (e.g., traditional legumes such as brown lentil, horse bean, and red bean) promotes diversified agriculture, with benefits for biodiversity, ecosystem services, carbon storage, and the agroecosystem's adaptation to stresses.

From a broad perspective, mountain agricultural adaptation to support food security requires systemic approaches that embrace livelihood diversification to reduce rural income sensitivity (Rosenzweig et al. 2020). In the dry Pamir, this entails investments in water management strategies that account for evolving cryosphere water sources, seasonal droughts, and episodic floods. Likewise, ensuring market access to farmers can help bridge the income gaps resulting from climate shocks (WFP 2017). Using neglected plants supports food security (Padulosi et al. 2011) when coupled with integrated restoration of degraded lands (Akhmadov et al. 2006).

Biodiversity and food security

Clearly, a greater diversity of edible plants, both cultivated and wild, strengthens food security in marginal regions whereby more diverse species mean more types of edible foods. Notably, a conspicuous lack of green vegetables are grown and consumed in the Pamir, particularly at higher elevations. Stresses on native species have come from overgrazing (Watanabe and Shirasaka 2018), poor agricultural practices (Sidle et al. 2019), shrub collecting for fuelwood (Breckle and Wucherer 2006), and warming climates (Ullmann et al. 2022). Pamir farmers generally recognize the health and taste benefits of biodiverse native crops and fruits, with the latter grown in marginal soils on rocky hillslopes (Giuliani et al. 2011). These species need protection from overgrazing and firewood collection to support not only home consumption but also value chain development, which is languishing.

Water issues

Climate is the primary regulator of water regimes that affect food production, but in the Pamir, water availability plays a more complex role (figure 2). Within Tajikistan, about 95% of agricultural land is irrigated; therefore, changes in water supplies greatly affect food security. The timing of water delivery to streams is critical because the summer months are dry.

Water supply dynamics

Water supplied to streams by snow, glacier, and permafrost melt is released more slowly, whereas rainfall contributes to

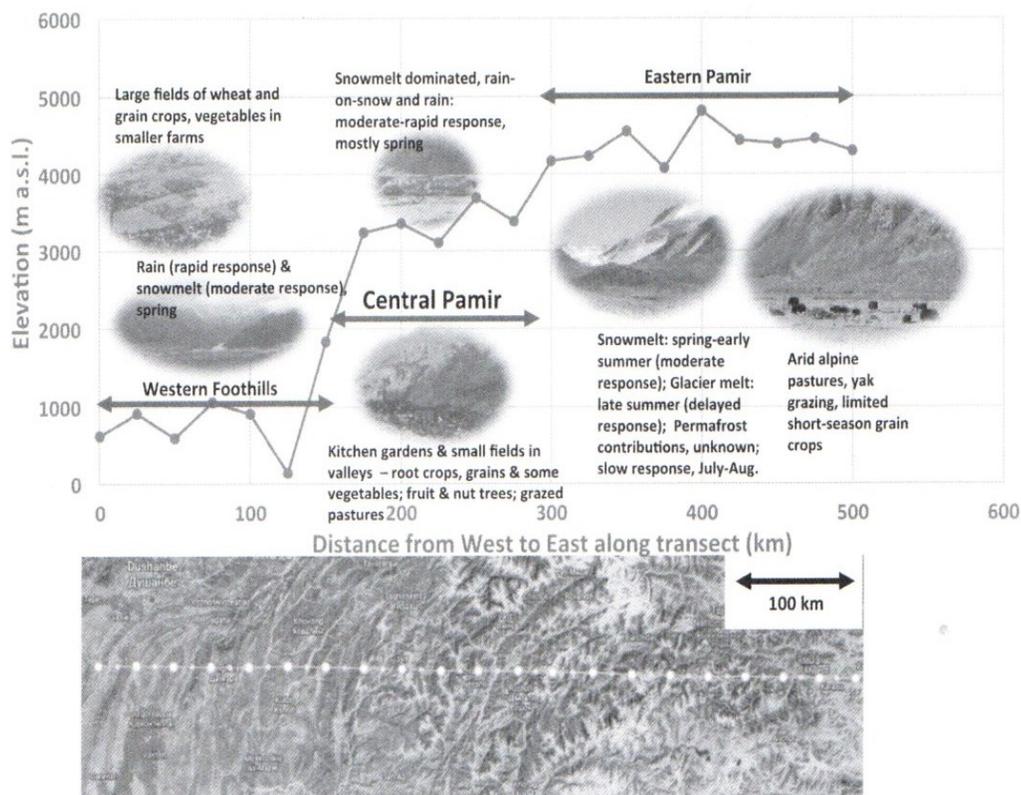


Figure 2. Elevation transect across the Pamir showing agriculture and grazing activities along with the dominant inputs of water (and their timing) in different zones. The lower image corresponds to the elevation transect in the upper graph.

runoff in near real time. Meltwaters are strongly conditioned by temperature regimes, and therefore, their relative contributions are affected by climate change (Immerzeel et al. 2010). Overall, snowmelt delivers the most water to streams, concentrated in spring through early summer, with the largest percentage of snowmelt runoff at high elevations; however, these are variable supplies from year to year. Although it is heavily emphasized in the climate change literature, glacier melt contributes far less runoff than snowmelt or rain: approximately 8% of the annual flow in the heavily glaciated Amu Darya basin (Armstrong et al. 2019). Nevertheless, glacier melt, where it is present, is important in late summer, when soils are dry. Permafrost is pervasive at high elevations in Central Asia (Gorbunov 1978), and the periodically thawing active layer overlying permafrost is a potential source of runoff in summer (Connon et al. 2014), albeit poorly documented (figure 2; Sidle 2021). Therefore, understanding the seasonal and interannual dynamics of these water supplies is essential to assess the availability and trends of irrigation water that support food security.

High plateaus and glaciated areas of the Eastern Pamir (more than 4000 m above sea level) have the lowest annual precipitation in the region. These arid lands support yak grazing and are among the most food insecure areas worldwide (Vanselow et al. 2012). Increasing temperature trends above 2000 m above sea level during the past 20 years typically occur in early winter and may therefore not greatly affect water supplies and food production because of frigid temperatures. At lower elevations in western Tajikistan, little temperature change coupled with increasing precipitation will likely augment water supplies and therefore agricultural production. Changes in the timing of rain and snowmelt pose concerns where higher elevations are experiencing declines in snow water in autumn, and the midelevations are shifting from snow to rain. Warming temperatures across the Central Pamir, coupled with snow water

decline, may induce water stress during dry years, affecting food security.

Connectivity of water sources to streams

Hydrological connectivity in mountain ecosystems is critical for the delivery of water from sources to streams, affecting the timing and amount of water supplied to fluvial systems. As various cryosphere sources change in a warming climate, understanding how these changes affect their connectivity to agricultural water supplies in summer is critical. Although hydrological connectivity has been recognized for decades and has been applied in linking runoff to streams in other environments, only minor attention has been paid to hydrological connectivity in the cryosphere (Ma et al. 2017), with no implications for agricultural water. Therefore, quantifying the connectivity of meltwater from glaciers and remote snowpacks to streams and rivers is important to assess their contributions.

A preliminary assessment in the Pamir that overlaid glaciated areas on a digital elevation model with streams delineated showed that only approximately 75% of glaciers are directly connected to channels. Melt from the unconnected glaciers and some of those feeding disconnected first-order channels may enhance rangeland soils but will not appreciably contribute to stream discharge that feeds downriver irrigation supplies supporting food security.

Irrigation efficiency and the potential for climate-smart water management

The efficiency of irrigation systems in Central Asia is low, with only 30% of water estimated to reach plant roots, and the average annual water used for irrigation is approximately 15,000 cubic meters per hectare (World Bank 2017). Other estimates suggest that 79% of irrigation water is lost, primarily by leakage from unlined and poorly maintained canals (World Bank 2004). The

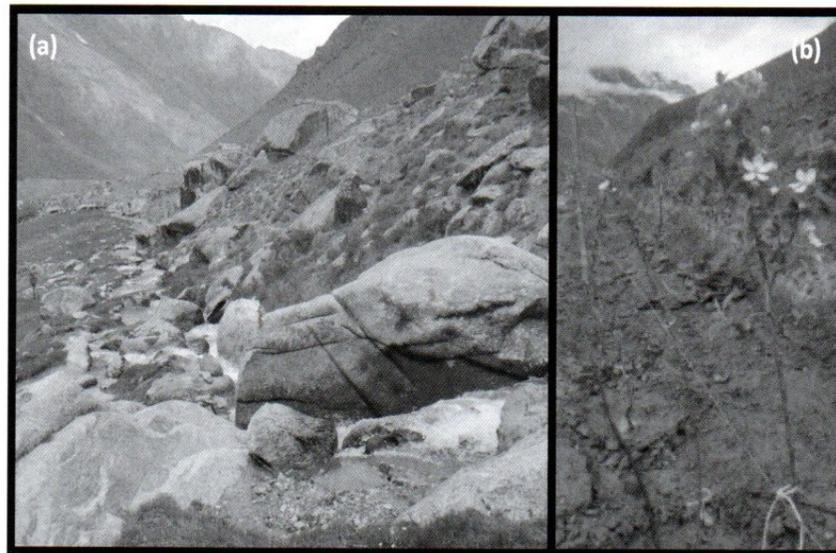


Figure 3. (a) Low-cost but inefficient irrigation canal in the Pamir delivering glacier and snowmelt runoff to small farms in Huff, GBAO (photograph: Roy Sidle) and (b) a simple drip irrigation system installed on a steep hillside in Vanj, Tajikistan (source: www.aarhus.tj).

extensive network of irrigation canals implemented during the Soviet era contributed to inefficient agricultural water use and subsequent deterioration of these systems since the Soviet collapse has affected mountain farmers who often use primitive unlined canals to deliver water to fields (De Martino et al. 2005; Sanginov and Akramov 2007) (figure 3a). Furthermore, excessive irrigation followed by high evaporation in summer causes salinization and soil degradation (Kulmatov et al. 2018).

The irrigated area in Tajikistan is estimated as 758,700 ha, but with an increasing population, the per capita area irrigated is decreasing, which is contributing to food insecurity (ALRT 2022). Therefore, water-efficient and better managed irrigation systems are needed to produce more food within the limited arable land. The major obstacles appear to be a lack of government financial support, the farmers' limited knowledge to maintain irrigation systems, low production of infertile soils, and unsustainable management of dry arable lands.

Flood and furrow irrigation constitute 85% of the irrigation practices in Tajikistan (Azizov et al. 2013). These methods are among the most water consuming, but high implementation costs of more efficient practices dissuade wide usage. Flood or furrow irrigation on steep slopes may induce soil erosion and landslides. The implementation of water-saving irrigation in the drylands of Tajikistan could save an estimated 1.6 cubic kilometers of water annually (Isaynov 2007). The improved management of irrigation and water resources will help farmers increase crop yields, supporting food security.

Drip irrigation is considered the most water-efficient system; however, it is too expensive and inaccessible for most smallholder farmers. Less expensive methods, such as gravity-fed irrigation, should be explored and promoted (Strong and Squires 2012). Drip irrigation may be a good alternative in steep regions that are not conducive to typical surface irrigation; the lesser and more efficient water applications should not adversely affect erosion (figure 3b). Water delivery in such small-scale systems can be economically facilitated by installing a water tank above the site, allowing sufficient hydraulic head to support drip irrigation instead of pumped water (Aarhus 2020).

Water and food security

Water supplies in Tajikistan are paradoxically related to food production; abundant water is produced from snowmelt and

glaciated areas, but these waters are released at different times, in spring through early autumn, depending on the elevation, with snowmelt highly variable from year to year. Furthermore, the precipitation and temperature trends that provide the source and release of water from the cryosphere vary throughout the Pamir, mandating site-specific estimates of available water during the late summer dry period, critical for food production. Although deep-rooted native plants adapt better to interannual changes in snowmelt, most cultivated crops require sustained irrigation, especially in mid- to late summer. The greatest long-term risks to food security appear to be in the Central Pamir and the Wakhan Corridor, where warmer temperatures and less precipitation (or no changes) will exert stresses on irrigation supplies and may even affect the migration of native plants (Khan et al. 2022). In the distant future, when the melting of small glaciers disconnects them from streams (or they completely melt), the downstream water supplies to farms will be greatly altered; however, most major glaciers in the Pamir are currently not at risk. Minor shifts from snow to rain may be occurring in midelevations of north and Central Pamir. These will affect the timing of water supplies; snowmelt is distributed over multiple weeks during spring and early summer, whereas rainfall contributes to runoff mostly in real time and requires immediate use or storage to take full advantage for food production.

Soil constraints

Because of high altitudes, cold temperatures, steep slopes, and sparse precipitation, Pamir soils are generally shallow (25–35 centimeters deep), with poor pedogenesis, low humus content (0.2%–0.3%), a coarse texture, and a weak structure (Cherbar 1971, Alikhanova et al. 1977). Higher organic matter contents are restricted to valley bottoms (Sanginov and Akramov 2007); the soils on steep adjacent hillsides are shallow or absent, with sparse vegetation and little organic matter. Spring rain and snowmelt support limited vegetation development and humus formation prior to the short growing season (Cherbar 1971). Slow physical weathering processes dominate over chemical weathering in these harsh environments (Egli et al. 2014). Dry summers desiccate the soils, reducing chemical weathering, microbial activity, and vegetation, which, in turn, inhibit soil development. Agriculture in these dry areas requires irrigation, which can affect soil

formation because the sediment in irrigation water deposits on the soils. With time, a new horizon forms, which is fundamentally different from pedogenesis derived from the underlying parent rock (Cherbar 1977). Alpine soils cover the mountain meadows and pastures in the Pamir (more than 3500 m above sea level). Because of the harsh climates, these soils are shallow, rocky, and infertile and are used only for grazing.

The soils in the foothills and lower elevations west of the high Pamir develop in a much warmer and wetter climate, with precipitation occurring mainly in winter and spring, augmenting soil moisture prior to the growing season (figure 2). The soil organic matter in this region increases with altitude, enhancing fertility (Tadjiev 1993). Mountain soils (1100 to 2500 m above sea level) have organic matter contents of 4%–6%, with dense grass cover in many areas. Although soil development is rather poor, these are among the most fertile soils of the region, supporting orchards and vineyards, and are the main areas of irrigated agriculture.

Colluvial, fluvial, and aeolian deposits

Colluvial deposits consist of gravity-transported sediments that often appear as debris fans at the base of hillslope channels. Because of high transport energy, these deposits are poorly sorted and require the removal of large boulders to prepare suitable cropland. Often, boulders are used to partition landholder plots, particularly in Afghanistan (figure 4a). Once the boulders are removed, the soils resemble contemporary fluvial soils—sand or silt matrices with coarse fragments and a weak structure (Khan et al. 2013). Debris fans support crop production until the next debris flow occurs.

From an agricultural perspective, fluvial deposits are mainly relics of past glacial activity, whereas contemporary river sediments occupy small areas near channels. Several of the largest irrigated areas in Tajikistan lie entirely on ancient fluvial deposits. Fluvial deposits are very different from residual soils in their structure, physical and geotechnical properties, hydrologic conditions, and fertility (Eliseev 1973). The texture of fluvial soils varies from sand to heavy clay. Given the flat topography, these soils are prone to water logging and salinity, sometimes necessitating artificial drainage (ADB 2021).

Deep loess deposits in the lower Vakhsh River basin extend down into the Khuroson and Yovon valleys of Khatlon, supporting Tajikistan's breadbasket (ADB 2021). Although this area is relatively food secure, spring rainfall makes these silty aeolian soils susceptible to erosion, particularly where soil organic carbon has been depleted following cropland abandonment (Wolfgramm et al. 2007). The greatest concern is increasing the development of deep gullies in these silty soils, which is associated partly with poor agricultural practices (Sidle et al. 2019, ADB 2021).

Improved and adapted agricultural management

Because most irrigation in Tajikistan occurs on sloping lands, excessive water applications accelerate soil erosion and impede agriculture. The irrigation of steeplands can change the chemical, physical, and biological properties of the soil (Cook 1988), and, coupled with poor tillage and compacted surfaces (roads, trails), gullies develop (Sidle et al. 2019). To ameliorate soil erosion and support food security, improved management measures are needed (Azizov et al. 2013).

Contour cultivation reduces soil erosion and has been used in Central Asia since ancient times. Terracing hillsides also reduces the runoff from steeplands (Azizov et al. 2013), but care must be

taken to avoid concentrating water in unstable sites where landslides can initiate (Sidle et al. 2006). In Tajikistan, terracing is used in hay fields and agroforestry plantations (Romer 2005). Two main agroforestry systems are used in Tajikistan: trees incorporated with arable crops and livestock grazing in mature forests (Romer 2005). Interrow tree plantations in arable lands are supported by government initiatives. In Fayzabad, Tajikistan, local farmers grow fruit trees in rows interspersed with vegetables or perennials to reduce soil loss (Bühlmann 2006). This improved ground cover, together with enhanced rhizosphere production, helps conserve soil and supports food security (Garrett et al. 2021).

No-till and minimum-till agriculture is not widespread in Tajikistan. Although these conservation practices preserve soil fertility, especially in rain-fed agriculture, weed growth makes them less favored among farmers. Nevertheless, these methods might be entry points for adaptation of conservation agriculture where no-till agriculture produced high yields of winter chickpeas in Tajikistan and Uzbekistan (16.87 and 22.55 tons per ha, respectively; Israilovich et al. 2019). Climate-smart agriculture, including water-saving irrigation systems, high-quality seeds, access to sustainable energy, and soil conservation practices, together with strengthening the financial positions of farmers and ensuring community-based governance and management of irrigation supplies (Dörre and Goibnazarov 2018), are important adaptation methods.

To maintain local supplies of nutritious foods and enrich soil fertility in mountain regions, diversifying crops with legumes is essential (Israilovich et al. 2019). However, recently, more than half of Tajikistan's irrigated lands have been planted in cotton, diminishing the diversification potential. The most fertile and flat areas are used for cotton and wheat, with little land remaining for other crops, negatively affecting food security.

Improving the pasture conditions in the arid, high Pamir is difficult and is complicated not only by harsh climate but also by anthropogenic pressures. Although the extent of the impact is questioned (Kraudzun et al. 2014), the removal of shrubs (including massive root systems of, e.g., *Ceratoides papposa*) for fuelwood along with overgrazing near villages has exacerbated wind erosion in Eastern Pamir (Breckle and Wucherer 2006, Watanabe and Shirasaka 2018). In the midelevation Pamir–Alay range, pastures are rapidly eroding because of the development and extension of deep gullies cut into glacial valley fills. Although overgrazing may exacerbate this natural process, little can be done to ameliorate such gully development, except for controlling runoff from roads and cattle trails.

Soil and food security

A major constraint on food production in the Pamir is the lack of arable soil. Incised valleys afford little flat to gently sloping land where soils can be cultivated, and many sites are affected by hazards. On steep hillslopes, the soils are typically rocky, shallow (or nonexistent), and infertile, making them unsuitable for most agriculture (figure 4b). Steep slopes where some soil exists may support native fruit and nut trees as sources of food.

Agricultural sustainability in Tajikistan is also compromised by soil erosion. Even in the Pamir foothills, where extensive croplands exist, arable land is disappearing via gully development. At higher elevations, natural water erosion processes exacerbated by overgrazing and poor cultivation compromise food security. The expansive Eastern Pamir plateau, with its poor and declining vegetation cover, is experiencing a downward spiral of soil loss by wind, making already marginal pastures unproductive. In such high

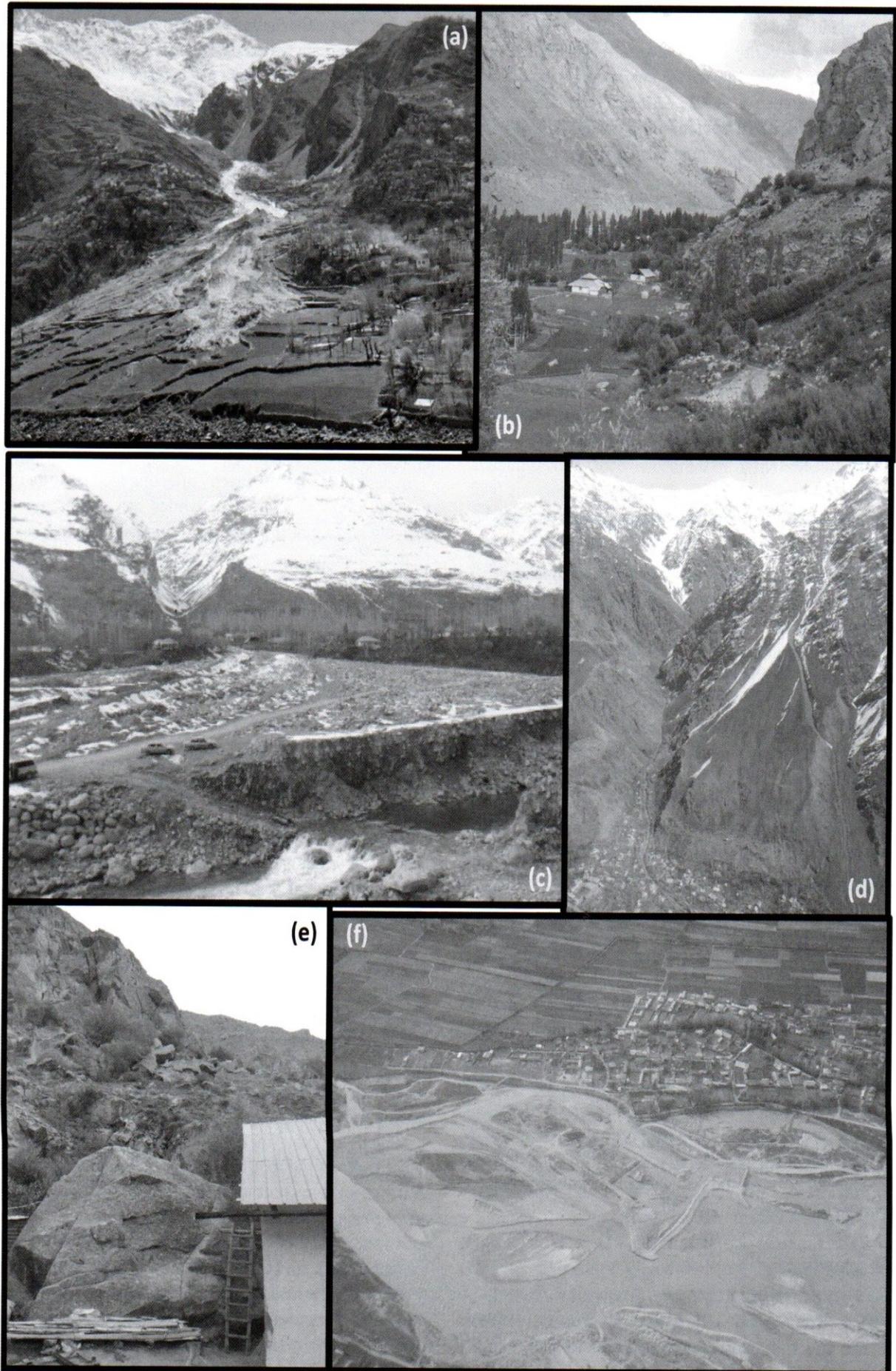


Figure 4. Examples natural hazards in the Pamir that affect villages and food security. (a) Active debris fan along the Panj River, Afghanistan, where crops are periodically destroyed by large debris flows and frequently affected by snow avalanches. (b) Roskala valley in GBAO, Tajikistan, with mass wasting on steep slopes adjacent to farmlands. (c) Obliteration of Barsem village, GBAO, Tajikistan, by a series of debris flows that occurred over multiple days in July 2015 believed to have been triggered by permafrost thaw around a glacier. (d) Moderate-size debris flow track (left of center) that periodically affects a Pamir village and small farms and a landslide to the right. (e) Large boulder from active rockfall putting residences and farms at risk. (f) Village and farmlands vulnerable to flooding along the lower Vakhsh River.

elevations where crops cannot be grown, yak grazing is the mainstay of food production.

To improve food security in this diverse region, agricultural innovations must be linked to robust and spatially explicit climate information (Romeo et al. 2020, FAO 2022). Very little can be done to improve the soils, except for reintroducing woody vegetation that eventually enhances humus. However, reversing the land degradation trajectories by introducing measures such as agroforestry, drought-adapted seeds, climate-smart irrigation, rotational grazing, reliance on native species, and reducing fuelwood collection will improve soil productivity in warming climates.

Geomorphic and cryosphere factors

Adjacent to the confined valleys, where most farms exist in the midelevation of the Pamir, the slopes are very rocky, with poor soil development (figure 4b). Various hazards (landslides, snow avalanches, debris flows, rockfall, glacial hazards) affect nearby farmlands (figure 4a–4e).

Geomorphic constraints and associated natural hazards

Mass wasting from slopes adjacent to valleys supplies both chronic and episodic sediment to agricultural lands; chronic sediment is supplied through dry ravel and progressive rockslides, and episodic sediment is supplied via larger landslides, debris flows, and rockfall. Small to medium-sized debris flows are very common on these steep slopes, initiating after coarse materials infill gully-incised slopes, triggered by snowmelt or rainfall (figure 4d). Debris flows in very steep gullies may initiate in the absence of these triggers once sufficient coarse materials accumulate. These coarse transported fragments do not augment soil productivity; rather, they hinder agriculture, negatively affecting food production and native vegetation. Occasionally, large rockfalls affect not only farmland but also residences (figure 4e).

The numerous farms on debris fans in the Pamir are a risk for food security (figure 4a). These fans represent the flattest terrain in many areas and are attractive sites for agriculture and residences. Debris fans experience periodic avulsions via debris flows, which completely reset the land surface and can destroy everything in their path (de Haas et al. 2018). Less steep, alluvial fans also experience avulsions during high flows (Scheinert et al. 2012). Although alluvial processes transport finer sediments, they may still reset the fan surface, affecting agriculture. A survey of a 42.5-kilometer road segment along the Gunt River showed nine major debris fans, with a mean surface area of 56.8 ha; all but one fan was occupied by farms and residences, indicating the risks to food security and livelihoods (Sidle 2020).

Flood hazards

In the high mountains, floods generate in several ways, with diverse impacts on food security. The most common causes of floods are extended and widespread rainfall, intense rainfall, rain on snow, and rapid snowmelt. Floods caused by widespread rainfall respond more slowly to rain, with the greatest impacts downriver, where wider floodplains become inundated; the depth, extent, and length of inundation determines the implications for food security (figure 4f). High-intensity storms fall on smaller areas and, if they are located over a steep headwater catchment, can cause destructive flash flooding within narrow riparian zones. Rain on snow and rapid snowmelt can generate both downriver inundation and flash floods in headwaters.

In all cases, flash floods cause more damage within the affected area, but the areal extent is more confined than that of downriver floods, where damage occurs by inundation across a wide area. Although blame has been focused on the role of climate change, much of the damage caused by flash floods in the high mountains is likely due to inappropriate expansion and development in the most flood-prone lands (figure 4f; Ziegler et al. 2016). The floods on alluvial fans are caused by rapid snowmelt, heavy rainfall, and rain-on-snow events but can also be exacerbated by rapid glacial melt. The most dramatic and damaging floods in the high mountains occur during glacial lake outburst floods (GLOFs) and by breaching landslide dams in channels (e.g., Mergili and Schneider 2011, Strom 2013); however, these are rare events. Floods associated with glacial melt and GLOFs will likely increase in a warming climate, posing greater downriver hazards and impacts on food security (Nie et al. 2021). Smaller floods also occur when large snow avalanches block rivers, causing inundation upstream and damage downstream when the rivers breach the avalanche deposits (Caiserman et al. 2022).

In addition to floods directly affecting food security in mountainous areas, agricultural activities can exacerbate flooding. Heaving grazing in the high mountain pastures has been linked to flash flooding due to cattle trampling that reduces the infiltration capacity of the soil, alters vegetation cover, and initiates gully formation, short-circuiting the runoff to streams (Sidle et al. 2019). Poor cultivation, such as compacting soil with heavy machinery and tilling perpendicular to contours, increases overland flow and flooding (Alaoui et al. 2018).

Snow avalanche hazards

Snow avalanches are dominant mountain hazards in winter and spring that directly affect food security. Because snow avalanches are among the fastest mass movements, their damages can rarely be avoided or mitigated, especially in the high mountains, where most valleys are at risk. Although some avalanche mapping and associated effects have been conducted in Central Asia (Kravtsova 1990, Bair et al. 2020), little is known about avalanche impacts on infrastructure and farms. Recently, the systematic mapping of avalanches using remote sensing archives was developed to assess the annual numbers and locations of the villages and roads affected by avalanches (Caiserman et al. 2022). This assessment in northern Afghanistan showed more than 800,000 large avalanche deposits proximate to villages and roads since 1990. As such, avalanches compromise food security in these areas.

Millions of cubic meters of snow accumulate in avalanche deposits along the foothills, where most farms exist. Although avalanches often occur in winter, they also occur in early spring, when sowing wheat or potatoes has commenced. The high velocity and weight of the snow destroys all planted crops in the avalanche path, and the farmers have no opportunity to recover these affected croplands (figure 4a). Furthermore, many large avalanches strip away the soil, which leaves the avalanche areas unproductive for years. Because mountain communities depend on these lands for subsistence, avalanche hazards threaten food security.

Another often overlooked aspect related to the food security–avalanche nexus is the impact of snow deposits on road connections and traffic in mountains. Mountain villages depend on roads for food and other supplies. Avalanches block roads several times every year in winter and early spring, delaying delivery of supplies. Depending on the number and size of avalanches, it can take several days to more than a week for authorities to clear roads

and enable traffic flow. In northern Afghanistan, 5.5% of the road network is affected by at least two large avalanches every year (Caiserman et al. 2022).

Glacial and permafrost hazards

GLOFs represent the most spectacular cryosphere hazards; however, these are more common in the Western Himalaya than in the Pamir (Mergili and Schneider 2011, Veh et al. 2020). GLOFs caused by debris flows that trigger tsunami-like waves breaching lake dams are risks in high mountains because of numerous glacier lakes (Gruber and Mergili 2013). One of the most destructive GLOFs in the Pamir occurred in Dasht in 2002, flooding the entire area and resulting in 24 fatalities. GLOFs affect food security because the flash floods and debris transported downstream damage farmlands and villages. Many high mountain valleys worldwide are vulnerable because of their exposure (Carrivick and Tweed 2016).

Warmer temperatures are the primary cause of GLOFs, causing an increased risk of glacier collapse into lakes because of melting ice. These hazards have been increasing, especially in Himalaya-Karakoram mountains, because of warming (Nie et al. 2021). With projected rising temperatures in Central Asia (Kraaijenbrink et al. 2017), the frequency of GLOF damage to farmlands will likely increase and threaten food security.

More common glacial hazards that affect agriculture, villages, and food security in the Pamir are glacier-related landslides and debris flows. These commonly occur during the spring snowmelt and rainfall, although they can be triggered during warm summer weather, when meltwater from glaciers and adjacent permafrost thaw occurs (figure 4c; Sattler et al. 2011, Peng et al. 2022). The rapid release of debris flows may prevent safe evacuation from runout areas; therefore, understanding the precursors that initiate such hazards (e.g., warm temperature, snowmelt, rainfall) and restricting infrastructure and housing development in runout zones are essential.

Permafrost in the Pamir typically begins at approximately 4000 m above sea level (Gorunov 1978), and there is an estimated 23,951 square kilometers of continuous permafrost terrain in the Panj and Vakhsh basins. Negative impacts of permafrost thaw on food security in a warming climate are virtually unknown, with the most likely being damage to infrastructure because of subsidence and mass wasting in degrading permafrost, affecting food distribution (Hjort et al. 2022). Warming temperatures may benefit food security by releasing more runoff from the permafrost thaw in late summer; however, the long-term dynamics are uncertain. High-elevation pasture production may also benefit from the thawing permafrost, tempered by increases in localized mass wasting and subsidence.

Natural hazards and food security

There is little information linking natural hazards to food security, but in the Pamir, these are intrinsically intertwined because of the proximity of croplands to steep hillslopes and rivers. Given that real-time prediction of hazards such as landslides, debris flows, rockfall, and snow avalanches is difficult even in highly instrumented areas, the prospects for assessing farmland vulnerability to such hazards in the rural Pamir are best informed by past inventories, the substrate, weather, and terrain characteristics. The vulnerabilities associated with the hazard-food security nexus are more prevalent in the Pamir than in similar terrain in developed countries, where affected valleys often have mitigation infrastructure to reduce the impacts. Given the importance

of small-scale agriculture in the Pamir, avalanches, debris flows, and floods represent challenges that endanger food security every year.

Social and economic considerations

Poverty abounds in the Pamir, with 87% of households below the calculated purchasing power parity poverty line of US\$2.15 per day. To cope, people resort to outmigration (Robinson and Guenther 2007) and external aid (Bredigkeit et al. 2020) for livelihood support. Following a decade of poverty decline, overall poverty in the mountainous GBAO increased by 19% from 2007 to 2009 (Akramov and Shreedhar 2012). Recent increasing fuel costs and civil unrest in GBAO, along with climate change will exacerbate such trends, increasing food insecurity.

Striking evidence in a 2021 survey in Tajikistan revealed that, although 16% of the households in urban areas were moderately or severely food insecure, 21% of the rural households were food insecure, and only 31% of were food secure (FAO 2022). Several factors contribute to the high level of food insecurity in this landlocked mountain region. Severe winters frequently affect transportation routes, affecting the supply chains, marketing, and commodity costs to mountain residents. Significant portions of rural household budgets are allocated for heating instead of for the procurement of food, and short summers yield only one crop of either wheat or potato, which is insufficient to meet the winter needs (Mislimshoeva et al. 2014, Kasymov et al. 2022). Other issues exacerbating food security include the exploitation of natural resources, unsustainable agricultural and grazing practices, and poor mountain road development, e.g., Chinese Belt and Road Initiative (Watanabe and Shirasaka 2018, Sidle 2020).

Food security issues and changes affecting high mountain communities

A major factor contributing to malnutrition in these high mountains is poor infant and child diets, with only 20% of the young children receiving adequate food diversity and meal frequency (Klassen et al. 2019). Micronutrient deficiencies remain major public health issues, with 53% of school children experiencing iodine deficiencies and 29% of young children being anemic (UNICEF 2012). The links among food security, poverty, and nutrition are profound; decreases in household income typically result in less money allocated for food, prompting negative coping strategies, such as purchasing cheaper and less nutritious food or buying less food.

The common stressors include insufficient nutritious food, high food prices, low incomes, no job opportunities, increasing population, increasing food demand, limited agricultural land, water limitations, harsh environments, new pests and diseases, and natural hazards (Hussain et al. 2016, Romeo et al. 2020). Some of these stressors are increasing with the changing climate in certain areas, affecting the scheduling of crops (Khakimov et al. 2020). Other food insecurity impacts among mountain people include hunger, famine, poor health, increased hospitalization, stunting, and childhood contagious diseases (UNICEF 2012). Socioeconomic status and accessibility to food are also concerns. Consequently, food insecurity weakens people by increasing mortality, diseases, and disabilities. It increases the direct economic costs of coping with health issues and reduces human potential and economic productivity.

What are the key economic challenges?

Mountain economies largely depend on agriculture. The lack of productive land, limited access to quality agricultural inputs and capital, poor knowledge of sustainable and adaptive agricultural practices, and the lack of infrastructure lead to food insecurity and threaten livelihoods. Food security is expected to worsen with rising food prices and remittance decreases due to the COVID-19 pandemic, the economic recession, and the Ukraine war. Limited financial investment in these impoverished rural regions is attributed to high transaction costs and risks, economies of scale, and poor infrastructure, among other factors (Ledgerwood and Wilson 2013, Lopez and Winkler 2018). Poor investment in agriculture poses additional problems following the abandonment of self-serving Soviet subsidies and the ensuing civil war in Tajikistan (Spoor 2018). Such challenges are further compounded by climate change.

Highlights of the socioeconomic–food security nexus

Aside from the obvious widespread poverty effects on food insecurity, rural communities in the Pamir have been and continue to be affected by many socioeconomic externalities. During the Soviet era (1920 through 1991), Tajik societies were artificially reorganized and depended on state subsidies for food, energy, and financial support, including infrastructure development (Kreutzmann 2002, Breu et al. 2005). The Soviet collapse created socioeconomic turmoil, with the removal of subsidies and the breakup of collective state farms prompting a return to smallholder subsistence

farms, which were generally too small to provide family food. The ensuing civil war in Tajikistan, followed by a series of sporadic conflicts, fueled food insecurity. The global food and financial crises that began in 2006 affected food security (Akramov and Shreedhar 2012), and this was exacerbated by the recent COVID pandemic, civil unrest, the supply chain effects of the Ukraine war, and the havoc wreaked by the Taliban takeover in Afghanistan. Although it was previously noted in the geographically and culturally diverse Pamir (Kassam 2009), we emphasize that robust place-based socioeconomic and biophysical knowledge needs to be applied in tandem to address the pressing food security concerns.

Moving toward an integrated approach

Tackling food insecurity in the Pamir and other mountain regions is a daunting task with many moving parts. The challenges facing poor mountain dwellers are more complex than those in other areas where improving agricultural production and biodiversity are core interventions. Although these aspects are important, high mountains with severe climates, numerous hazards, and land constraints require a broader approach to address acute and increasing food insecurity. These issues, coupled with the uncertain climate and its associated water supplies, place this region among the most vulnerable because of short growing seasons and dry summers. In the present article, we map the stressors affecting food security in the Pamir in the continuum from natural to anthropogenic to assess the potential pathways for reversing the current downward spiral (figure 5).

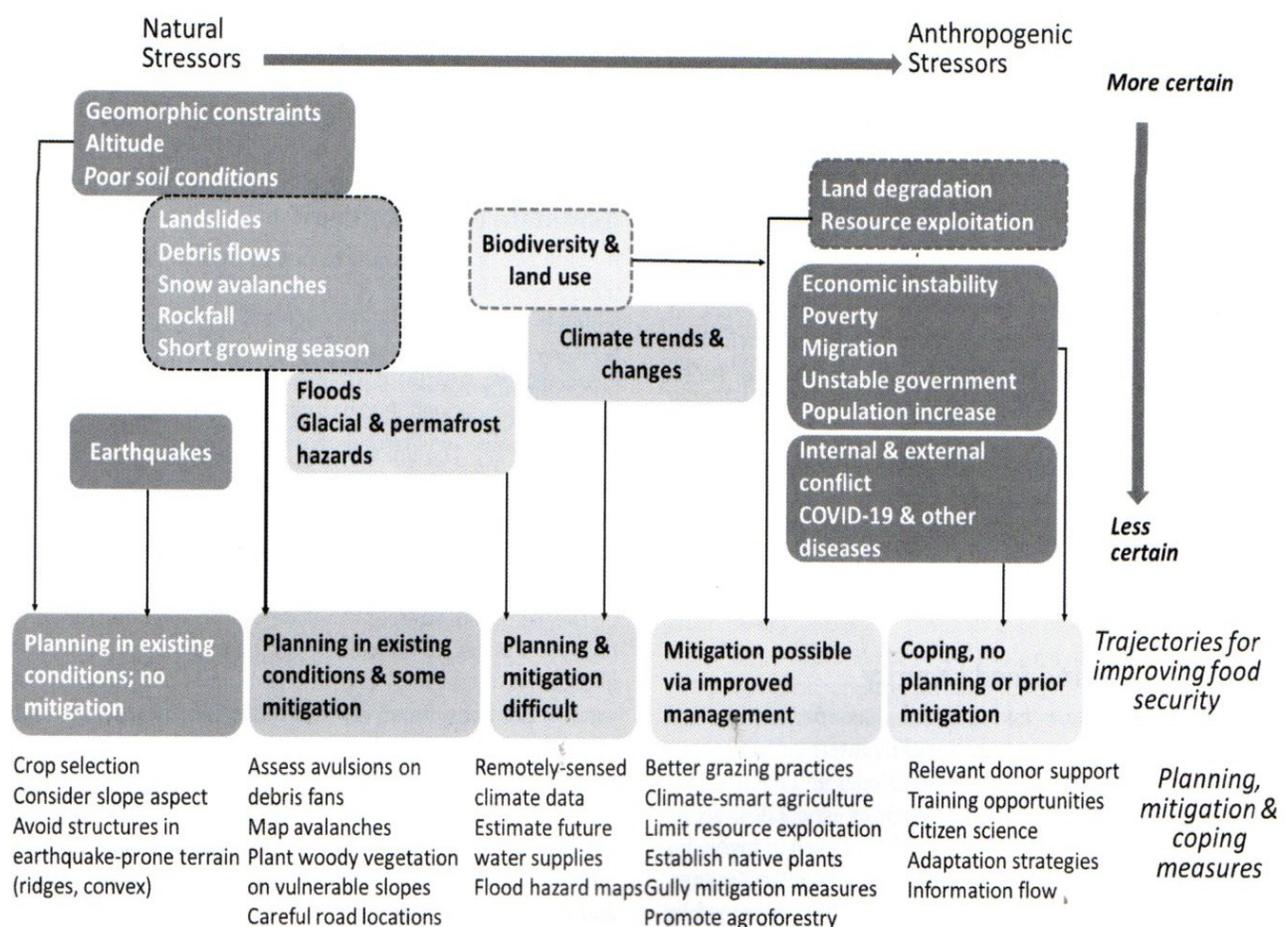


Figure 5. Conceptualization of how various stressors in the continuum from natural to anthropogenic affect food security in high mountains, including which are more certain in the future and which are less certain. The blue stippled outlines refer to stressors that can be mitigated by better land management; the black stippled outlines denote stressors that are somewhat affected by land management and can partially be mitigated; the yellow outlines show stressors partly affected by land use or climate change but not easily mitigated; and the stressors without outlines are either unpredictable or cannot be mitigated without major effort. Some stressors can be mitigated by improved management, whereas others must incorporate appropriate planning or coping measures (the orange boxes in the lower portion of the diagram).

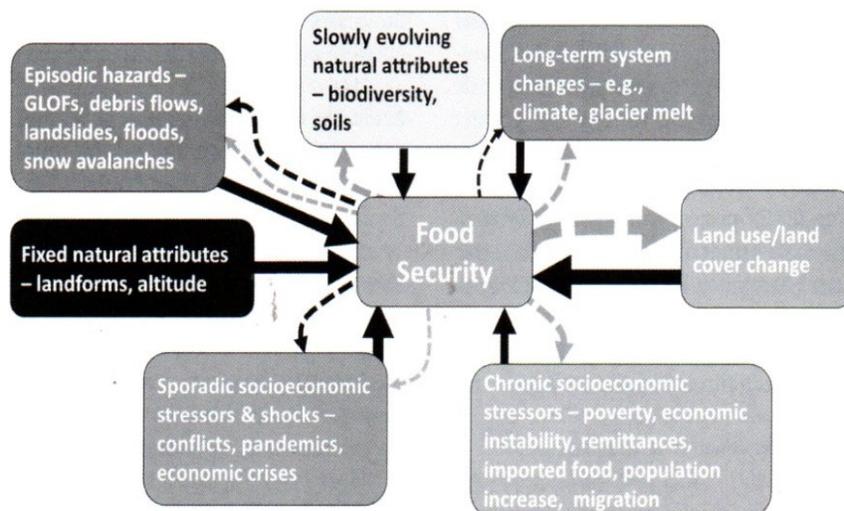


Figure 6. Natural, biophysical, and socioeconomic stressors affecting food security in the Pamir with feedback loops. The relative impacts of the various stressors on food security are reflected in the thickness of the solid arrows. Feedback loops (shown with broken arrows) indicate the extent to which stressors can be ameliorated by land management (the green broken arrows), social and economic reforms (the red broken arrows), and land-use planning or infrastructure measures (the black broken arrows). The thickness of these feedback loop arrows reflects the extent to which they can successfully address food security.

Effective solutions to food insecurity in the Pamir must consider multiple factors that vary across the region. Understanding environmental change and assessing the degree to which various anthropogenic stressors contribute to food insecurity and how and to what extent these stressors can be ameliorated by land management, socioeconomic reforms, and planning is critical (figure 6). For example, although the constraints imposed by natural attributes such as confined valleys and high elevations cannot be mitigated, the land use in floodplains can be adapted by planting fruit and nut trees that will not be damaged by occasional flooding, and remotely sensed climate data can be used to inform agriculture adaptations. In addition, positive feedback loops to alleviate poverty and malnutrition may inform livelihood changes (e.g., less reliance on imported food coupled with producing biodiverse nutritious vegetables; figure 6). Another relevant example in the Pamir involves better land-use planning, low-cost infrastructure, and social reforms related to the use of debris fans. Understanding the frequency and spatial extent of debris flow avulsions and snow avalanche impacts (episodic hazards; figure 6) on these fans can strengthen food security by restricting buildings on the fans, constructing low-cost berms to reduce the spread of avulsions, and adapting agricultural strategies according to the severity of the hazard. This will also require social changes (adjusting to new cropping strategies) and economic support. Other challenges relate to long-term changes in climate and water availability that are critical for food production, including adjusting to the increasing droughts that affect farms and pastures, as well as biodiversity.

The residents of the high Pamir are most vulnerable to food insecurity because of the severe climate, the short growing seasons, their poor diets, the small size of their land holdings, overgrazed pastures, and access problems. The complicating socioeconomic issues include extreme poverty, rising fuel costs, fuelwood gathering, currency devaluation, regional conflict, and the small number of jobs. More diverse diets are needed to reverse childhood stunting and malnutrition. In the high rangelands, where crops cannot be cultivated, a focus on sustainable pasture management and livestock is needed. In addition to climate and biophysical barriers, the Pamir residents experience immense socioeconomic stresses.

Combining sound scientific information on static and dynamic environmental constraints with socioeconomic trajectories

is needed to develop the most productive pathways to foster food security. Understanding the intertwining nature of these issues, including developing relevant feedback loops to adaptation measures such as land management, socioeconomic reforms, planning, and infrastructure (figure 6) is critical to craft sustainable approaches that support food security in mountain communities. This robust, place-based information cannot be achieved by a one-size-fits-all model.

As a next step, we propose a type of expert system to analyze these factors by incorporating multiple decision points, starting with the geographic setting and progressing to environmental constraints (e.g., climate, available arable land, hazards), place-based amelioration measures (e.g., gully mitigation, reestablishing native species, climate-smart irrigation), local social stressors, livelihood enhancements (e.g., value-chain development), adaptation strategies, and possible governmental and external support. The feedback loops in figure 6 represent a general guideline of which technical and social interventions are most promising to reduce food insecurity. Although we have outlined some of these planning, mitigation, and coping strategies (see the bottom of figure 5), none of them can be viewed in isolation; rather, an integrated, place-based approach is needed, such as an expert system that will incorporate scientific details and interactions behind a firewall in a user-friendly system for local governments, communities, and donors. Developing this system for the Pamir will require external support that relies on sound scientific information; recent spatially-distributed climate information; recognition of social stressors and local knowledge; training; and engagement of mountain communities to ensure effective knowledge dissemination and implementation. Without these commitments, such interventions will likely not succeed.

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