

POTATO CROP RISK IN A MOUNTAIN FARMING SYSTEM: WHAT GROWERS' KNOWLEDGE CORRECTS IN LAND EVALUATION

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ABSTRACT. Potato Crop Risk in a Mountain Farming System: What Growers' Knowledge Corrects in Land Evaluation. We establish what a multi-criteria land evaluation model can and cannot say about the risk that decides whether a strategic crop is kept at the local scale, and what growers' knowledge corrects. The case is Rîșca commune, 6564 ha in the Apuseni Mountains, where potato is the main cash crop and is grown without irrigation. The model retains the crop-specific scoring curves of the official Romanian land evaluation methodology for six indicators and runs them under four aggregation rules, with weights taken only from external sources; agreement is reported after correcting for the areal share of each class. Hazard enters as a daily series for 59 grid cells over 1990–2025, resolved by phenological window; exposure comes from 277 parcels declared under potato (103.57 ha) and from sites mapped by growers; the qualitative component comes from eleven narrative interviews. Slope alone sets the class for 58.4% of the modelled area and is part of the limiting factor for 64.8%, whereas climatic indicators are the sole limiting factor for 8.6%. Almost half of the area actually cropped, 45.5%, falls in the two lowest classes of the official instrument. The two hazards never coincide in thirty-six years, but the expected coincidence is below half a year, so compound behaviour cannot be determined at this scale. Changing the aggregation rule shifts the level of the scores without changing the ranking of land units; an imported weight set re-ranks them. Under three of the four rules, the classification places more than 73% of the area in a single class, and agreement with growers' judgement can no longer be tested. The qualitative component corrects two inferences that the spatial data alone would have supported: that the area declared each year measures the crop that is

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maintained, and that the silence of the interpolated field on topographic position means the phenomenon is absent. The agreement protocol prevents a third: that agreement with grower-indicated parcels validates the model. Most constraints invoked in decisions to withdraw from the crop are non-climatic risk drivers, which an assessment built on land suitability does not contain.

Keywords: climate risk, vulnerability, exposure, agroclimatic hazard, multi-criteria decision analysis (MCDA), farmers' local knowledge, Apuseni Mountains, *Solanum tuberosum*

1. INTRODUCTION

Crop losses attributed to drought and heatwaves in Europe tripled, from 2.2% in 1964–1990 to 7.3% in 1991–2015. Across the 28 drought events in that period, European cereal yields fell by 9% on average, but the interquartile range of responses runs from +2% to –23% (Brás et al., 2021): the size of an event does not by itself determine the loss. The European climate risk assessment rates the risk to crop production as substantial for Europe as a whole in the 2021–2040 horizon and as critical for southern Europe over the same horizon (Dentener et al., 2024). Both figures are continental aggregates, while the decision to keep growing a crop is made at the parcel level. What is lost between the two scales is the information that decision needs: whether the hazard falls in the window in which the crop is vulnerable.

For potato, the difference appears at the phenological stage level. The European assessment attributes large productivity declines to drought and high temperatures that coincide with critical crop stages (Dentener et al., 2024). The European framework for compound extremes in potato states its limit at exactly this point: the duration, magnitude, intensity and return period it computes describe properties of meteorological events, not phenological stages, and phenological resolution is left as an extension (Gohari et al., 2026). The gap is one of scale and of temporal resolution. We address it in part, through indicators resolved by phenological window, without characterising compound events with the framework's metrics (Section 5.5).

A farm's margin also depends on what it can change in its own practice. Smallholders are assessed as more vulnerable to climate change impacts than large farms (Bezner Kerr et al., 2022), and the constraints that stop them from investing do not belong to the land (HLPE, 2013). Regions with low adaptive capacity cluster in the central and eastern part of the continent (European Environment Agency, 2024), where irrigation is rarer than in the south and rain-fed farming is more exposed to drought (Trabucco et al., 2024). In southern Romania between 1990 and 2005, the decline of arable land was more than six times greater on slopes than on flat land (Kuemmerle et al., 2009).

Potato is the crop in which biophysical and economic exposure overlap most closely. Europe produces a quarter of world production (van Loon et al., 2025), with the highest per capita consumption in the east (Pllana et al., 2018). An ensemble of nine crop models gives a 4.6% fall in dry-matter yield for each degree Celsius of warming (Fleisher et al., 2017), and the European analysis of compound extremes uses thresholds of 30 °C for heat stress and 5 °C for cold stress (Gohari et al., 2026). In Romania the cropped area fell from 196,000 ha in 2017 to about 76,000 ha in 2024, and self-sufficiency from 100.3% in 2017 to 48.1% in 2023 (Stoicea et al., 2025). The country has moved from net exporter to net importer of potatoes.

For the administration, a supply problem turns into a question about land: where can potatoes still be grown? The answer passes through a single instrument, the evaluation of agricultural land (Section 2.3), and for potatoes it performs poorly. Within the areas actually cropped, the suitable classes account for only half of the surface, and the index does not predict actual yields — for wheat, maize and sunflower, counties with a higher index also have higher mean yields, but not for potato (Patriche et al., 2024). The instrument measures the agronomic aptitude of the land, not the risk to which the crop on it is exposed. Its two climatic factors are annual means, the resolution at which the phenological window disappears.

The current alternative, multi-criteria decision analysis (MCDA), changes the decision rule without solving the problem of verification. The benchmark remains the area actually cropped, and the premise behind it becomes questionable where cropping decisions follow markets, labour and access (Akpoti et al., 2019; Section 2.3). When growers' knowledge is brought in, its timing decides what it can show: used before the model, it calibrates, and a test applied afterwards is no longer independent of it (Section 2.4). Where it has entered at the end, agreement with the map has been measured with correlation coefficients, which show whether two rankings run in the same direction but not how much of the match would have occurred anyway because one class covers a large part of the territory. We have not found such a correction in the studies we consulted, and without it an apparently perfect agreement cannot be told apart from an artefact of class shares.

Rîșca commune, in the Apuseni Mountains, was chosen because potato has been grown there for generations, and the open question is what is happening to the crop now. The system is one of small, scattered parcels on a plateau cut by valleys, with potato as the main cash crop, no irrigation, and a distance of 44 km to Cluj-Napoca. A risk assessment in such a system requires two things that a spatial model does not produce: a comparison that does not start from current land use, and an account of the constraints that are not properties of the land. Narrative interviews supply both — parcels indicated by

those who work them, and the stated reasons for withdrawal — and they also date the event that mattered.

The study has four objectives:

1. to characterise the local agroclimatic hazard by phenological window from daily climate series, and to establish what growers' accounts can and cannot document when set against these series;
2. to build a GIS-based multi-criteria model of land suitability for potato and to report how much the classification changes when the aggregation rule and the weight set are changed;
3. to compare the model output with the current distribution of the crop as recorded by the administration, judging the match against the share of the land that each class occupies;
4. to document the constraints that growers invoke in their decisions, to establish which of them can and which cannot be represented spatially, and to identify the inferences that would have been unsupported if drawn from the spatial model alone.

The contribution concerns the relation between the two sources. Two inferences that would have been drawn from the spatial data alone turn out to be unsupported once set against growers' accounts, and a third, drawn from the comparison with growers' parcels, does not survive correction for chance agreement; the demonstration is in Section 5.1. The official instrument enters the discussion through two readings: read as present aptitude, a suitability index says little about a mountain territory; read as the distance to a constraint, it becomes a risk indicator. The constraints growers invoke are divided by their spatial status, and the division is made operational in Section 3.4.

2. CONCEPTUAL FRAMEWORK

The European risk assessment decomposes climate risk to a crop into hazard, exposure and vulnerability, and vulnerability further into sensitivity and adaptive capacity; alongside climatic hazards, the framework explicitly retains a category of non-climatic risk drivers (European Environment Agency, 2024). We adopt this decomposition. Hazard enters as daily climate series computed by phenological window (Section 4.1). Exposure enters as the area declared under potato and as the sites indicated by growers (Sections 4.3 and 4.6). Vulnerability enters through the constraints that decide whether the land is still worked, and those invoked most often belong to the framework's non-climatic category (Sections 4.5 and 5.2).

2.1 Climatic hazard for potato and the problem of scale

Heat and water hazards affect potato through the phenological stages they coincide with. Water deficit translates into fewer tubers, smaller tubers or both, depending on genotype and crop stage (Deblonde & Ledent, 2001;

Schafleitner et al., 2007). Late blight pressure also does not follow temperature linearly: the pathogen's thermal optimum lies below that of the crop, and losses depend on the timing of infection (González-Jiménez et al., 2023). Biotic hazard is not part of the model and returns only in the qualitative component.

Moving to the commune scale requires figures that the national scale does not provide. Digital suitability mapping for Romania supplies three (Patriche et al., 2024): mean annual temperature rose by 1.27 °C between 1961–1990 and 1990–2019, a value obtained by comparing two different climate products, a qualification the authors state; the largest increases are in the lowlands, up to 1.6 °C, and the mountain zone is absent from their list; in the Carpathians the most pronounced change is in precipitation, 118.8 mm per year, the largest in the country. Two observations are ours. The direction of the Carpathian change, more water, is not the one suggested by the continental framing in terms of drought and heat. And where the altitudinal range is small, spatial variation in the climatic component comes from the slope and aspect corrections, not from the climate field itself.

2.2 Adaptive capacity and its non-climatic limits

A thermal margin is not an advantage in itself: it matters only to a farm that can change something in its practice. The crop-level adaptation repertoire is documented — cultivar, planting calendar, production system — and cultivar performance depends on the system in which it is grown (Pszczółkowski et al., 2026). Using it requires capital, information and water, which a small rain-fed farm does not have.

What decides whether the repertoire is used lies outside climate. In a consultation of 203 growers and specialists from six European pedoclimatic regions, the obstacles named for moving to sustainable practices were lack of knowledge, need for technical advice, complexity of practices and cost (Morugán-Coronado et al., 2024), and their ranking depends on who is asked: for potato cropping systems in Iran, experts weight the ecological dimension more heavily and farmers the economic one (Rezaei et al., 2018). In Romania, a survey of 286 growers found labour shortage to be the most often invoked obstacle, cited by 75.5% of respondents, ahead of lack of technology at 68.2%, while climate does not appear among the first (Petrescu-Mag et al., 2022). All these rankings come from other contexts. What growers in a mountain system invoke, and in what order, remains an empirical question.

The European framework treats such constraints as non-climatic risk drivers rather than as background conditions (European Environment Agency, 2024). The distinction has a consequence for assessment: a farm that leaves the crop is no longer exposed, so the constraints that decide withdrawal enter the risk assessment on the same footing as climatic hazard.

2.3 What land suitability can and cannot measure

The instrument with which the administration answers the question about land records nothing of this kind. Agricultural land suitability in Romania is assessed with a quantitative methodology from the 1980s, still applied today by the County Offices for Pedological and Agrochemical Studies at scales of 1:5000 and 1:10,000 (Florea et al., 1987; Patriche et al., 2024), with a system of indices and scores taken over from Teaci and co-workers (cited in Florea et al., 1987). The bonitation score is the product of seventeen crop-specific coefficients below unity, each taking values in steps of one tenth between 0 and 1, which makes it non-compensatory (Dornik et al., 2024). A zero coefficient cancels the score, and a small one reduces it in the same proportion, however favourable the other factors are (calculation details in Section 3.3).

For potato, the coefficients place the thermal optimum in the submontane belt, with the maximum value over the interval 7.1–9.0 °C (Florea et al., 1987). Land that lies in this interval today has nowhere higher to go: if the corrected mean annual temperature exceeds 9.0 °C, the climatic coefficient falls, although neither the land nor its properties have changed.

National-scale application shows the limits of the model precisely for potato (Section 1). One of the authors' explanations is specific to this crop. Its suitability has declined recently due to warming, while cropped areas have remained the same by tradition (Patriche et al., 2024). The system uses eleven edaphic factors out of seventeen and is therefore finer on soil than on climate; the same authors propose three revisions: factors for drought, extreme precipitation and frost; means over the growing season; and partial indices by factor group, combined with group weights.

The last revision leads to MCDA, in which weights are derived from pairwise comparisons and applied through weighted linear combination (Saaty, 1980; Malczewski, 1999). What changes is the decision rule, not the data. On the same edaphic data, a parametric index and an additive index with fuzzy-AHP weights allocate the area quite differently, yet correlate almost identically with observed potato yields (Keshavarzi et al., 2020). Compensation also works in space: in a mountain case, the low weight of altitude let suitability appear in isolated patches at high elevation, which the authors removed with a binary exclusion mask applied after the weighted overlay, using a threshold of 2600 m for potato (Mejlumyan et al., 2026).

Both rules are then checked in the same way, by comparison with current land use — a common practice whose premise was formulated for extensive farming in sub-Saharan Africa, where cropping largely follows environmental conditions (Akpoti et al., 2019). At the scale of temperate continental Europe, the overlap is not confirmed. Wheat and maize occur on land of marginal suitability, while potato leaves large suitable regions with small cropped areas (Dornik et al., 2024). The official methodology is an

ecological model that uses only natural land conditions, without land improvements or socio-economic data (Dornik et al., 2024). Used as a proxy for exposure, it identifies suitable land, not the exposed household.

2.4 Farmers' narratives: spatialised knowledge, the ranking of constraints, adaptation as process

The second source outside the model is not cartographic. Farmers' local knowledge has entered biophysical land evaluation as a source complementary to measurement, and what measurement cannot replace is temporal variation: the frequency of rare events where no instrumental series exist, reconstructed from at least twenty years of observation in a catchment on the Loess Plateau (Messing & Hoang Fagerström, 2001). Elicitation can also remove criteria. In the same study, slope aspect was dropped from the evaluation because farmers deliberately spread the same crop over both aspects as insurance against interannual variability. Criteria that emerge under open elicitation often fall outside the biophysical list — slope microclimate and the location of frost damage, confined to the broad valleys (Cools et al., 2003), the cropping season as a first-order factor (Sicat et al., 2005), spontaneous vegetation as an indicator of soil class (Zapata-Muñoz et al., 2022).

Where these data sit in the workflow, however, decides what they can show. Used before the model, they calibrate: class limits are adjusted to conditions on the farms or to participants' experience and the evaluation is rerun (Ziadat & Sultan, 2011; Cruz-Bello & Romero, 2025), so a later test is no longer independent. Used after the model, they test, but agreement has so far been reported through correlation coefficients between stated perception and suitability class (Neswati et al., 2023; Jaman et al., 2025), without reference to the share of each class in the agricultural area.

What narratives can document has a limit in principle. Climate change is not directly observable, being an average over long periods; its local manifestations are what people can perceive (Spence et al., 2011). The link also runs the other way. Prior belief influences what people report as their own experience, so an account remains evidence about perception, not about trend (Weber, 2013). Comparison with instrumental series yields neither systematic agreement nor systematic disagreement, and where accounts diverge, the difference has been attributed to distance and altitude offset from the station (Reyes-García et al., 2024). Their functions in this study are stated in Section 3.7.

3. METHODOLOGY

3.1 Study area

Rîșca commune covers 6564 ha in the west of Cluj County, on the right bank of the Someșul Cald river, in the Gilău Mountains, a subunit of the Apuseni Mountains (Fig. 1).

Altitude ranges from 515 to 1166 m but is asymmetrically distributed: the mean is 944 m and the median 954 m. Most of the territory lies at around 950 m, on plateau-like interfluves cut by narrow, deep valleys. Mean slope is 15.8°, with a maximum of 54.9°. Valley sides generally exceed 19°, whereas the interfluvial plateaus stay below this value. Gently sloping land lies in the upper altitudinal belt and steep land on the valley sides.

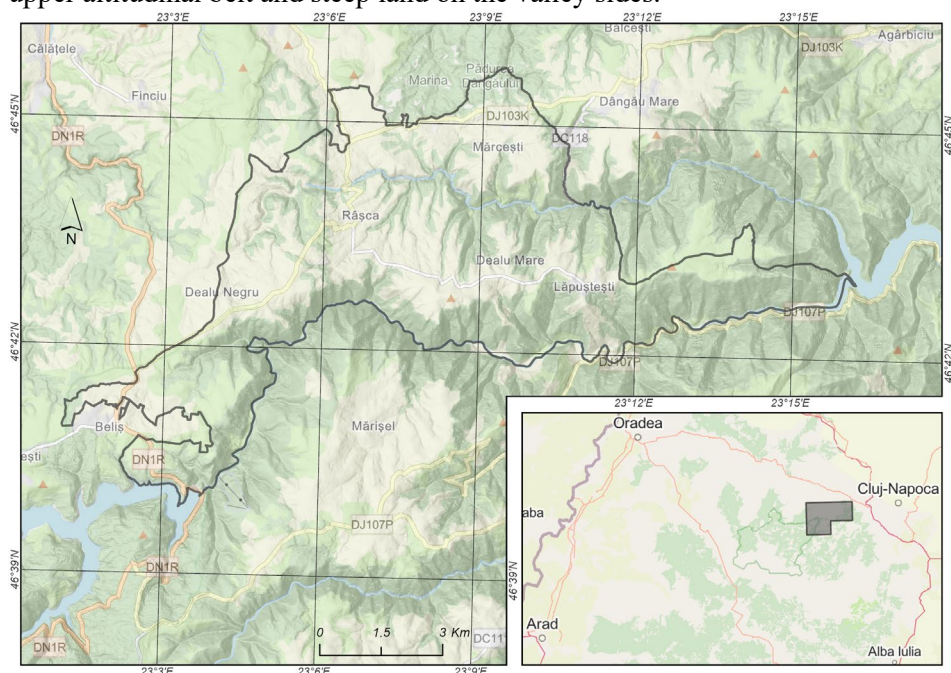


Fig. 1. Location of Rîșca commune in the Apuseni Mountains, with the nearest major towns — Cluj-Napoca, Oradea and Arad. Basemap: OpenStreetMap (© OpenStreetMap contributors), which spells the commune name Râșca; the text uses the form Rîșca, as in the soil survey of the commune (Bakos et al., 2008). Basemap labels cannot be moved or edited; the truncated label at the left edge of the inset is Békéscsaba (Hungary). The graticule labels refer to the main map.

Topographic position can act against altitude: in a dissected plateau relief, cold air collects at night in the deep valleys, so the interfluves may have a less restrictive thermal regime than their elevation would suggest, especially for late frosts.

The south-west of the commune, 1023 ha or one sixth of the territory, belongs to the Apuseni Natural Park and to Natura 2000 sites and is covered by coniferous forest and by grassland above 1000 m.

3.2 Research design and data

The study follows a convergent parallel mixed-methods design: the spatial and qualitative components were conducted independently and integrated after both were complete, using the protocol described in Section 3.7.

The commune scale is a condition of applicability. The European assessment finds that regional production variations offset one another at Union level and that aggregate risk falls through this compensation (Dentener et al., 2024), so the decision unit disappears from the analysis. The input data available here, a 1:10,000 soil survey and parcels located by growers, allow operations that national assessments cannot perform.

The layers used, with the source, resolution, version and role of each in the analysis, are listed in Tab. 1. All were projected to the Romanian national system, Stereographic 1970 (EPSG 3844).

Tab. 1. Data layers used, with the source, resolution, period and role of each in the analysis.

Layer	Source	Scale / resolution	Period	Role in the analysis
Soil units	Soil survey (Bakos et al., 2008)	1:10.000	2008	Soil volume, humus reserve, reaction, texture, erosion
Soil units, infill	Soil Map of Romania, sheet 10 Cluj (L-34-XII) (Florea & Asvadurov, 1994)	1:200.000	soil data from 1973; 1994 edition	Covers forest and built-up land; 10.7% of the modelled area
Digital elevation model	Copernicus DEM GLO-30 (European Space Agency, n.d.)	30 m	2011–2015	Slope; aspect for the thermal correction
Climate field	EMO-1 (Salamon et al., 2026)	~1.5 km	1990–2025	Mean annual temperature and precipitation; daily indicators (Section 4.1)
Land cover	CLCplus Backbone 2023 (European Environment Agency, 2025)	10 m	2023	Delimitation of the modelled area, 2846.2 ha
Declared parcels	Single payment applications, Paying and Intervention Agency for Agriculture, Cluj County Centre	parcel	2026 campaign	Crop exposure: 277 parcels, 103.57 ha
Narrated sites	Web map, indicated by respondents	point	2026	12 sites from 7 households

The soil layer combines two digitised sources of different resolution. The 1:10,000 soil survey covers agricultural land, with determinations for each soil unit (Bakos et al., 2008); where it gives no detail, that is, for forest and built-up land, units were taken from the 1:200,000 soil map, with local additions in particular cases such as the lake areas in the south-west and south-east.

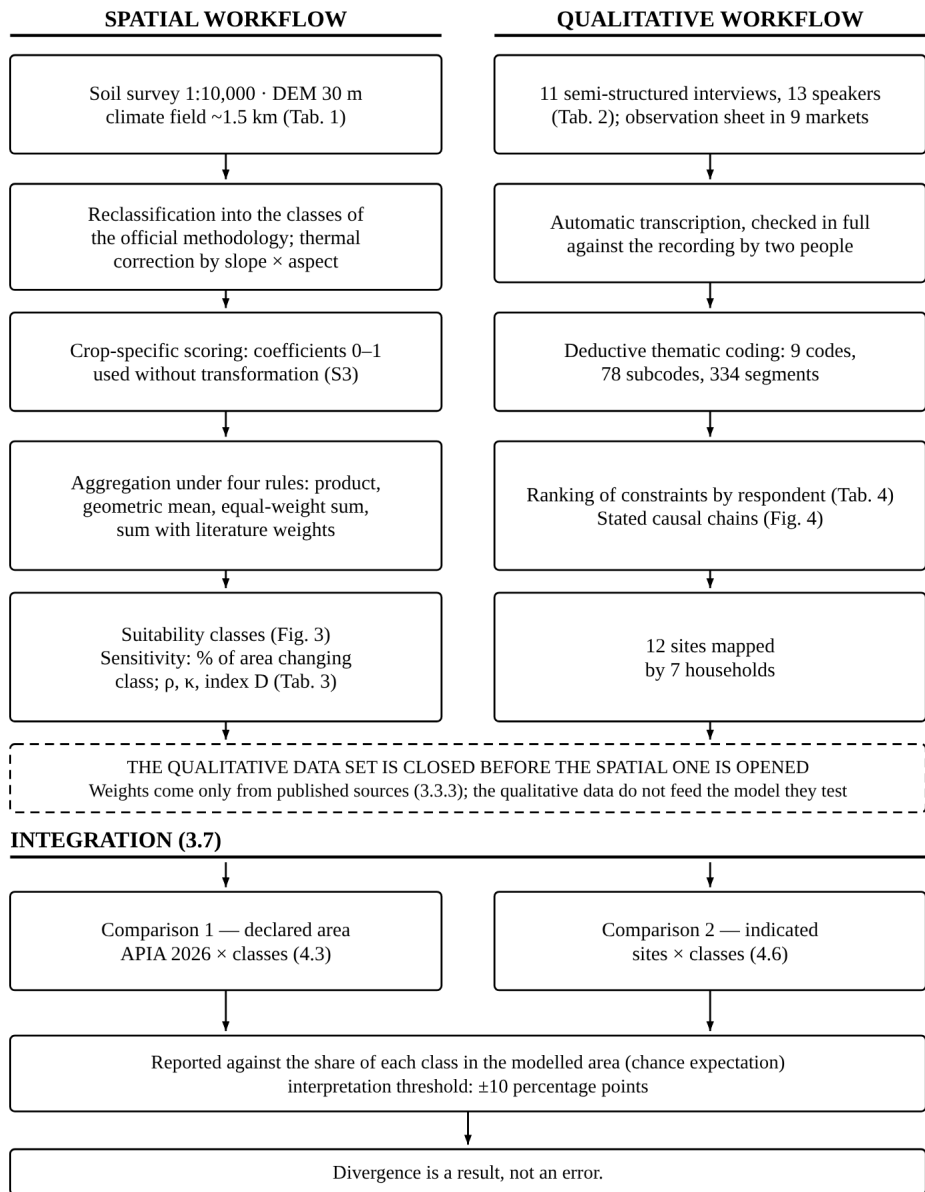


Fig. 2. Workflow. The spatial and qualitative components run in parallel; the dotted bar marks the point at which the qualitative data set is closed, before the spatial one is opened. Below it are the two separate comparisons described in Section 3.7. The figure is black and white by design.

Polygons taken over in this way carry no determinations of their own. The effect on the results is bounded. Of the modelled area, 89.3% comes from the detailed survey, and of the area declared under potato, 99.2%.

The coverage of the bonitation layer is given in S9. The layers are not contemporaneous, and the offset is stated: soil determinations date from 2008, the climate series covers 1990–2025, land cover refers to 2023, and the declared parcels to the 2026 campaign. The soil properties retained change slowly, but reaction and humus reserve depend on management and may have changed over the eighteen years since.

The sites indicated by growers were collected as points on a web map that displayed the parcels declared under potato to the paying agency over satellite imagery; where no declared parcel existed, respondents identified the parcel on the imagery by its boundary with neighbouring land. Positional accuracy depends on the imagery and on the scale at which each respondent placed the marker, was not measured and is reported as undetermined. The model classes were not displayed. The paying agency provided parcels without farm or farmer identifiers, with only the declared geometry and area; the conditions of publication are described in the data availability statement.

3.3 The suitability model

The model scores six of the seventeen indicators provided for in the methodology: slope, soil reaction, useful soil volume, humus reserve, corrected mean annual temperature and mean annual precipitation. Selection followed two criteria, in this order: the existence of determinations in the 1:10,000 soil survey, and discriminating power checked on the study territory. Total porosity, salinisation and alkalinisation have no determinations in the source. Of the remaining indicators, groundwater depth places 97.3% of the territory in a single class, gleyic units cover 1.2%, and texture yields two steps on a ten-step scale; none of them separates the area. The checks are documented in S9. The parsimony of the model follows from a check on the territory, and only in part from missing data.

3.3.1 Climatic indicators

Climate enters the model through the two climatic factors of the official methodology, mean annual temperature and mean annual precipitation. The means come from EMO-1, the European daily gridded data set at about 1.5 km (Salamon et al., 2026). The paper describing EMO-1 is still a preprint under open review in Earth System Science Data. From the data set we estimated the vertical temperature and precipitation gradients and applied them to the elevation model, so that the annual means follow relief at the resolution of the DEM. The methodology provides a topoclimatic correction for both: temperature by slope and aspect, precipitation by slope and soil permeability

(Florea et al., 1987). We applied only the thermal correction, following the potential insolation model rather than the methodology's class matrix: reclassified aspect and slope grids were multiplied, and the product was assigned to insolation–shading steps calculated for the growing season at 45° N (Stanciu, 1981; Tîrlă, 2012), which then adjusted mean annual temperature (values in S6).

Precipitation entered as the gridded annual mean, without the methodology's topoclimatic correction, and was scored on the class table of the corrected indicator (S3.2, S3.3); its spatial variation comes only from the altitudinal gradient and stays narrow. The differentiation added by the corrections therefore comes entirely from the thermal component, and it is large: within the 500–650 m band, four temperature classes coexist, from 8–9 to 11–11.7 °C. Neither the gridded data nor the corrections contain a term for topographic position, so the mechanism described in Section 3.1 remains outside the model (Section 5.5).

The official precipitation curve was preferred because it is the only one calibrated for Romania and the only one that penalises excess water. The climate layer is nearly uniform at the scale of the commune and is kept so that the procedure remains transferable.

The daily indicators used in Section 4.1 are not part of the scoring and come from the same data set at its native resolution. We extracted all 59 cells that overlap the commune, however small the overlap. The data set covers 1990–2025.

A dry spell is defined as an unbroken run of at least three days with precipitation below 1 mm, and a frost day as a day with a minimum temperature at or below zero between 1 February and 30 June. Aggregation by phenological stage follows the design of potato phenology models, in which frost risk depends on the date of emergence and emergence on the planting date (Pulatov et al., 2015, for northern Europe). The critical stages for potato are tuber initiation and tuber bulking (Gohari et al., 2026). We used 1–20 April for planting and 15 May–15 July for tuberisation; these calendar limits remain a working convention, since we did not find a Romanian full-text source that fixes them for a mountain Carpathian site. In each year the extraction covers the period from the second half of March to the end of July, so the maximum spell reported is the maximum within that period, not within the calendar year.

3.3.2 Scoring and aggregation

From the official methodology we kept the crop-specific scoring curves and the exclusion thresholds, and we replaced the aggregation rule. We used the bonitation coefficients, with values in the interval [0; 1], without transformation, by reclassifying the value classes into the coefficients published

for potato (S3). Any non-linear transformation applied to an already calibrated curve would have required a separate justification, which we do not have.

In the official methodology, the bonitation score under natural conditions is calculated as the product of the coefficients multiplied by one hundred (Florea et al., 1987):

$$NB_{\text{prod}} = 100 \cdot X_1 \cdot X_2 \cdot X_3 \cdot X_4 \cdot X_5 \cdot X_6 \quad (1)$$

As a product of factors between 0 and 1, score (1) is less than or equal to each coefficient, and with six factors it falls systematically well below them. To compare the multiplicative rule with an additive aggregation on the same scale, we also expressed it as a geometric mean:

$$NB_{\text{geom}} = 100 \cdot (X_1 \cdot X_2 \cdot X_3 \cdot X_4 \cdot X_5 \cdot X_6)^{1/6} \quad (2)$$

As a monotonic transformation of the product, Eq. (2) preserves the ranking of land units given by Eq. (1); only the scale changes. Additive aggregation, recommended by Patriche et al. (2024) in place of the plain product, was applied as a weighted linear combination:

$$NB_{\text{sum}} = 100 \cdot (w_1 X_1 + w_2 X_2 + w_3 X_3 + w_4 X_4 + w_5 X_5 + w_6 X_6) \quad (3)$$

The divergence between the two rules is fully explained by the dispersion of a land unit's coefficients, because the geometric mean equals the arithmetic mean if and only if all coefficients are equal. We quantified this dispersion with an imbalance index:

$$D = 1 - NB_{\text{geom}}/NB_{\text{sum}} \quad (4)$$

where $X_1 \dots X_6$ are the bonitation coefficients of the six scored indicators, with values in the interval $[0; 1]$; $w_1 \dots w_6$ are the corresponding weights, summing to one; NB_{prod} is the score calculated with the multiplicative rule; NB_{geom} is the same score expressed as a geometric mean; NB_{sum} is the score calculated by weighted linear combination; and D is the imbalance index of the coefficient profile, calculated for Eq. (3) with equal weights. Scores were divided into five classes in steps of twenty points: 81–100, 61–80, 41–60, 21–40 and 0–20. The limits were applied to the integer score, identically for all four runs, with the first class the most suitable (Florea et al., 1987). This is the grouping provided for summary maps, which the methodology labels with the letters A to E; we number the classes here with Roman numerals I to V. The detailed grouping, ten classes in steps of ten points, is reported in S5.

Changing the rule changes the meaning of the score, not only its value. Under a weighted sum, the non-compensatory curve described in Section 2.3 becomes compensatory, so a severely limiting factor can be offset by the others. The curves were calibrated for the first situation. The limitation is discussed in Section 5.5.

The methodology's only climatic exclusion threshold, a corrected mean annual temperature below 4 °C, is never reached on the modelled area, whose lowest class is 6–7 °C; water and forest leave the analysis through the delimitation of the modelled area (Section 4.2). Slope remains a compensatory factor, because a slope threshold would reintroduce the multiplicative rule we are replacing.

3.3.3 Weights and weighting scenarios

The weights come only from the published literature; the qualitative component plays no part in setting them. The choice follows from the design of the comparison: weights derived from the same respondents whose parcels are later compared with the model output would make the test in Section 4.6 dependent on calibration.

The literature on potato weights is scattered, and complete sets that include climatic and relief criteria are rare. We took a single weight set from the literature, while keeping the Romanian scoring curves; it was obtained through the analytic hierarchy process, with seven criteria and a consistency ratio of 0.09, and calibrated in a high catchment of the Trans-Mexican Volcanic Belt at 1800–4640 m (Ceballos-Silva & López-Blanco, 2003). The other two complete sets we identified do not map onto the six indicators scored here: thirteen criteria from fifteen experts for Armenian mountain agriculture (Mejlumyan et al., 2026) and sixteen sub-criteria from northern Peru (Iliquín Trigos et al., 2020). The pedoclimatic settings of all three differ from the Carpathian arc, and the difference is stated wherever they are used.

We ran two weighting scenarios. The first assigns equal weights and serves as the reference; it is not a neutral assumption, but the difference from the second scenario measures how much of the classification comes from the weights. The second uses the Mexican weights, mapped onto the six indicators and renormalised: 0.404 for useful soil volume, 0.185 for precipitation, 0.133 each for soil reaction and humus reserve, 0.120 for temperature and 0.025 for slope. The three mapping decisions behind these values are set out in S9; each is a choice, not a deduction, and their combined effect is reported in Section 4.4.

The divergence between published evaluation systems is on its own a reason to report several scenarios. For the same crop, slope receives 0.0239 of the total weight in the Mexican evaluation, the smallest value among the seven criteria. In the Romanian methodology, it is the criterion that reduces the potato coefficient most, from 1.0 to 0.1 across the classes of rugged terrain. This is not an error in either source; it follows from calibration on territories with different mechanisation thresholds and farm structures.

3.4 Exposure and adaptive capacity

We documented the current distribution of the crop from two sources. The first is administrative: the parcels declared under potato in the single payment applications of the 2026 campaign, obtained for the commune's territory. The second is our own: the sites that respondents indicated on the map as their best parcels. The partial overlap between the two sets is reported as a result.

The comparison between the model and the current distribution is presented as an agreement analysis, not as an accuracy assessment. It yields three situations to interpret: suitable land with the crop present, suitable land without the crop, and unsuitable land with the crop present. Their shares do not measure model performance. The procedure follows the cross-tabulation of suitability and land use applied to potato and maize in the Toluca Valley, where the mismatch was reported as a result (Ceballos-Silva & López-Blanco, 2003).

The administrative source covers a single cropping season, whereas the hazard we assess is defined over decades. The limitation is not only one of time offset: growers rotate crops, so a parcel in rotation appears in a given season under another crop code, and land left fallow does not appear as potato land at all. A multi-year series would reduce the first problem without solving the second.

The constraints growers invoke fall into two classes with different spatial status. Parcel size and shape, the degree of microrelief fragmentation, road quality and distance to the collection point are properties of the land and have coefficients published in the official methodology, in a correction layer applied after the natural score. Manuring history, household labour, the existence of a successor, a customer base and storage capacity are not properties of the land and cannot enter as its attributes. The former remain outside the model because of data availability, not in principle (Section 5.4); the latter remain in the qualitative component by their nature.

3.5 Sensitivity and uncertainty analysis

A model that scores climate in discrete classes is not deterministic. Among nine crop models run at the same sites, temperature is the component on which they diverge most (Fleisher et al., 2017), and uncertainty reporting remains rare, in 38 of 166 synthesised assessments (Akpoti et al., 2019).

We ran the model under two aggregation rules and two weighting scenarios, on the same modelled area. We report the share of the area that changes class relative to the reference scenario, the agreement between classifications measured by Spearman's coefficient and by quadratically weighted kappa, and the imbalance index of Eq. (4). A share of the modelled area, rather than absolute area per class, makes the result comparable across studies (Li & Chen, 2020).

3.6 Qualitative data: collection, analysis, ethics

The qualitative component ran in parallel with the spatial one and was integrated with it after both were complete (Section 3.7; Fetter et al., 2013). Between 19 May and 4 August 2026 we applied two semi-structured interview guides, one for growers in the commune and one for vendors in the food markets of Cluj-Napoca, and an observation sheet; the guides are reproduced in S1 and S2, and both end with a mapping step.

Recruitment followed two routes: in the commune, from telephone numbers of growers identified online, with further referrals from respondents; in the food markets of Cluj-Napoca, by approaching the vendors present on the day of the visit. This yielded eleven interviews with thirteen speakers, one of them held jointly with three members of the same household. Interviews with growers from the commune took place in Rîșca village, the commune centre, and in the markets of Huedin and Cluj-Napoca, where some of them were selling; the outlying villages of the commune were not covered. The sample spans four categories: seven growers from the commune, a representative of the local administration who himself grows less than one hectare of potato, two growers from outside the commune and one trader (Tab. 2). The last three respondents act as a contrast group that separates what belongs to the study site from what belongs to a position in the marketing chain. Quotations in the text are the authors' translations from Romanian; the original wording is given in S7.

Code	Date	Respondent type	Category	Pers.	Setting
I1	19.05.2026	Grower	From the commune	1	Household
I2	19.05.2026	Grower	From the commune	3	Household
I3	19.05.2026	Grower	From the commune	1	Household
I4	19.05.2026	Grower	From the commune	1	Household
I5	22.05.2026	Local administration representative, grows under 1 ha	Institutional	1	Telephone
I6	02.08.2026	Grower	From the commune	1	Household
I7	03.08.2026	Grower	From the commune	1	Market
I8	03.08.2026	Grower	From the commune	1	Market
I9	03–04.08.2026	Grower	From outside the commune	1	Market
I10	03–04.08.2026	Grower	From outside the commune	1	Market
I11	03–04.08.2026	Trader	Reseller	1	Market

Tab. 2. Interviews by respondent category. Interview I2 was held jointly with three members of the same household; the total is 11 interviews with 13 speakers.

We recorded interviews with verbal consent obtained before recording, transcribed them automatically (TurboScribe) and corrected each transcript by hand against the recording. Two of the authors completed the observation sheet in nine food markets in Cluj-Napoca on 3 and 4 August 2026, counting stalls selling potatoes and written claims of origin from the commune; the sheet follows audit instruments for the food environment (Glanz et al., 2007; Byker Shanks et al., 2015), and its protocol is given in S9.

The interviews were analysed thematically and deductively. The coding frame was derived from the themes of the guide, and the coding unit was the segment expressing a single idea. This produced nine main codes and seventy-eight subcodes, with 334 coded segments. The codes cover the components of risk assessment (S9). Segments that contradict the dominant theme were retained and coded separately rather than treated as outliers; two subcodes serve this purpose explicitly, one recording the denial of perceived climate change, the other disputing the distinctiveness of the local produce.

Because the code frame derives from the guide, code frequencies partly reflect the structure of the instrument. This concerns the ranking of factors reported in Section 4.5, where one open item asks respondents to name the important factors themselves and the next item offers them a list. The ranking rests on the first item only; answers to the second are partly an artefact of the question.

The sites marked as points on the web map, inside or outside a parcel received from APIA, were compared with the model classes following the protocol in Section 3.7.

3.7 Integration and agreement protocol

The qualitative component has three logically distinct functions, stated before the analysis. The first is comparative: the parcels that growers name as their best are compared with the model classes. The second is explanatory: the constraints invoked in decisions to expand or withdraw describe what the model does not contain. The third concerns the exposure source, which is limited to a single season (Section 3.4).

Coding of the interviews was completed before the model results were consulted, so that the treatment of growers' judgement would not be influenced by the suitability classes (Section 2.4).

Agreement is reported against the share of each class in the modelled area, that is, against chance expectation: if a class covers 60% of the area, the fact that six of ten indicated parcels fall in it carries no information. We set the threshold at ten percentage points above or below expectation; below it, we report the result as descriptive. The consequence extends to the model itself. A classification that assigns almost the whole territory to a single class cannot be

tested against an outside judgement, whatever the actual state of the land, and agreement is assessed only under classifications that separate the territory.

Integration is presented in joint displays (Sections 4.5 and 4.6; Guetterman et al., 2015). Divergence is a result, not an error.

One limitation of the protocol is stated here; the others are in Section 5.5. The indicated sites are only those considered good, so they sample one tail of the distribution; poor land can be assessed only through the administrative source.

4. RESULTS

4.1 The climatic component: model inputs and comparison with farmers' memory

Dry spells were extracted for each of the 59 climate cells that intersect the commune, for 1990–2025, using the definition in Section 3.3.1. The cells are not independent observations: statistics across them describe the spatial extent of a spell, not the sample size; the unit of analysis remains the year.

The annual value is the median, across the 59 cells, of each cell's longest spell. Its median over the thirty-six years is ten days, with minima of five days in 1995 and 1999 and a maximum of twenty-two in 2019 (S4). The regression slope is 1.07 days per decade, with a confidence interval that includes zero (−0.18 to +2.31); the series does not support a lengthening of dry spells.

The comparison with growers' accounts concerns one particular year. Water deficit during the critical stage is the hazard invoked most often in the corpus, and the wording ties it to a year and a moment: “last year, for instance, there was a drought. You can't irrigate. [...] It's no use spraying and doing everything if it doesn't rain and you have no water just when the potato has to grow” (I1). The year invoked, 2025, contains two spells of more than ten days in the tuberisation window — 8–17 June and 29 June–8 July — present on all 59 cells. Of the thirty-six years in the series, only two have a spell of at least ten days falling entirely within the tuberisation window on a majority of cells: 1996, on 32 of the 59, and 2025, on all of them. Under a looser criterion, one to nine cells, three further years qualify, and 2017 would then coincide with a late frost (S4).

The years that go unmentioned do not settle the question. The longest spells in the series, in 2019 and 2020 (twenty-two and twenty-one days), both end before tuberisation. The grower who names 2025 is speaking of the year before the interview, so the match may reflect recency rather than selection by phenological window. A second grower places the most severe drought four or five years before the interview (I8), in years without a ten-day spell inside the window on a majority of cells; a day with 2–3 mm of rain ends a spell under the

1 mm threshold without relieving a drought, so the indicator can split one dry period into several. The accounts document perceptions, not a climatic trend.

Frost days were extracted with the same procedure. The median date of the last frost is 12 April, with extremes of 19 March in 2010 and 25 May in 1991, and the slope of -3.70 days per decade towards an earlier last frost has a confidence interval that includes zero.

The exposure of the crop is read from the position of this date relative to the planting window. The last frost falls after 1 April in twenty-nine of the thirty-six years and after 20 April in eight. Planting at the start of the window assumed here is exposed in more than four years out of five. Of those eight years, three — 1991, 2007 and 2017 — have two or more separate frost events after 20 April, so the account of planting too early and then suffering two frosts describes a rare pattern, not a common one.

The frost episode described in most detail has no counterpart in the series. The respondent dates it to the year before the interview: fine weather on 1 May, then frost, and shoots found blackened three weeks later (I2). In 2025 the series has no frost on any cell after 12 April, a limitation of daily air minima interpolated at about 1.5 km, which do not record ground frost or cold-air pooling (Section 5.5). Conversely, the series records late frosts that respondents do not mention; the most extensive in May, on 2 and 3 May 2007, covers 109 cell-days.

The two hazards do not coincide. A dry spell of at least ten days in the tuberisation window occurs in two years out of thirty-six, a last frost after 20 April in eight, and no year has both. The expected number under independence is 0.44 years, so the absence of coincidence does not document a negative dependence. Both events are rare, and thirty-six years cannot decide whether they attract or exclude each other.

The spatial distribution of the last-frost date, however, follows altitude almost perfectly: across the 59 cells, the correlation between altitude and the median last-frost date is 0.96, with a delay of 2.4 days per hundred metres. No departure appears in the low valleys, although there the mechanism respondents describe — night-time pooling of cold air on the valley floor — would produce the opposite effect. The high correlation is largely built in. The data set applies an orographic correction to temperature with a fixed lapse rate of 0.006 K m^{-1} before interpolation, so altitude enters as a predictor with an imposed slope, not one estimated from stations; the delay of 2.4 days per hundred metres reproduces this lapse rate more than an observed property of the area. The distinction one respondent draws between parcels, “not up on the ridge either, where the drought burns” (I1), describes a mechanism that lies outside the model.

4.2 Land suitability

The model was run on 2846.2 ha of herbaceous and low shrub vegetation, delimited from the European land cover layer. We preferred a public cartographic product to our own digitisation, because the procedure must remain applicable in other administrative units without visual interpretation work; as a consequence, the mask includes pasture and hay meadow alongside arable land, a limitation stated in Section 5.5. The excluded classes are listed in S9.

Under the multiplicative rule of the official methodology, the modelled area is distributed over the suitability classes as follows: class I, 3 ha; class II, 176 ha; class III, 1104 ha, or 38.8%; class IV, 953 ha, 33.5%; class V, 610 ha, 21.4% (S5). The suitable classes account for 6.3% of the modelled area, and the two middle classes for 72.3%. Over the whole territory, forest included, the share of class V rises to 55.1%. The two figures have different denominators. The second includes the forested slopes, where slope is steepest and the crop absent, so a statistic computed for the administrative unit more than doubles the constraint that bears on the cultivable area.

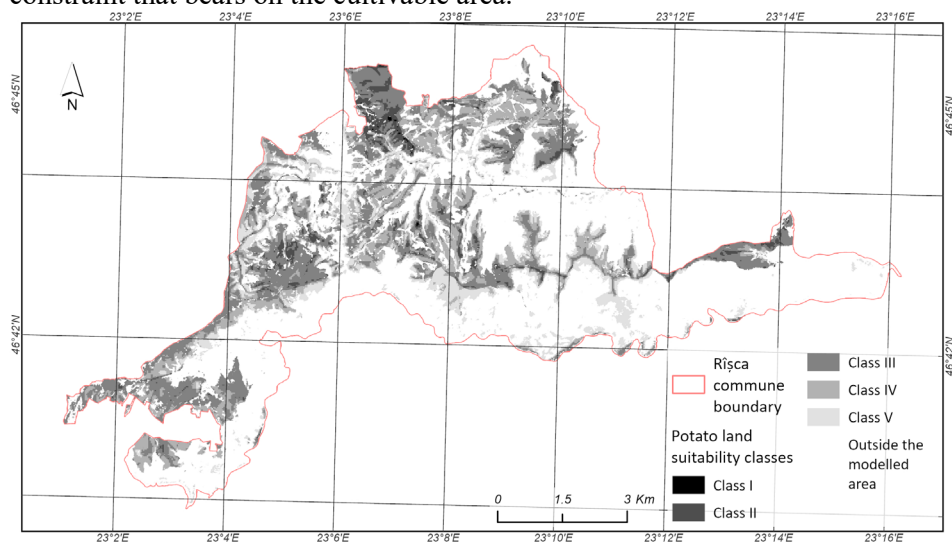


Fig. 3. Suitability classes for potato in Rîșca commune, obtained with the multiplicative rule of the official methodology. The published layer is described in S8.

Low scores come mostly from a single indicator. On 58.4% of the modelled area, the minimum coefficient of the profile belongs to slope alone; soil reaction together with precipitation limits 14.0%, precipitation alone 8.6%, and humus reserve 6.9%. Adding the cases in which slope reaches the minimum jointly with another factor, slope is part of the limiting factor on 64.8% of the modelled area and on 81.6% of the whole territory. Eighteen per cent of the

modelled area has a slope coefficient below 0.5, and under the product rule a single slope class in the upper range reduces the score to one fifth, regardless of soil quality. In our six-indicator implementation of the official instrument, the classification is determined mostly by slope. It is also the input most exposed to measurement error (Section 5.5).

The thermal factor differentiates weakly within the commune. Corrected mean annual temperature spans six classes of the indicator, but the potato coefficient takes only two values. On 81.7% of the modelled area, which lies on the 7.1–9.0 °C plateau, the coefficient is 1.0; on the rest it is 0.9, split between 13.1% below the plateau and 5.2% above it. Its contribution to the internal order of the classes is small but not zero, and temperature is never the sole limiting factor. The 5.2% already above 9.0 °C is the land on which the thermal constraint is present, not projected.

The alternative aggregation rules shift the level of suitability upwards, by amounts that differ between scenarios (Tab. 3). How much of this shift affects the ranking of land units, and not only their level, is reported in Section 4.4.

4.3 Exposure and agreement analysis

The single-payment applications for the 2026 campaign include 277 parcels declared under potato within the commune, totalling 103.57 ha, or 3.6% of the modelled area.

Agreement was reported using the rule in Section 3.7. The area declared under potato is under-represented in the lowest class by 10.8 percentage points — 10.6% against an expectation of 21.4% — and over-represented in class III by 6.8 points. The other three deviations stay below three points. The only deviation that exceeds the ten-point threshold set in Section 3.7 therefore concerns the lowest class; across the intermediate classes, the distribution of the cropped area cannot be told apart from chance expectation. The deviation cannot be attributed entirely to growers' choice: the reference mask includes pasture on steep slopes, so the 10.8 points partly measure the difference between pasture and arable land (Section 5.5). The administrative source therefore does not support an inference about growers' choices.

The three analytical situations are unevenly distributed. Suitable land without a declared crop covers 170.3 ha, or 94.9% of the land in classes I and II. Unsuitable land with the crop present totals 47.16 ha, 45.5% of the declared area: almost half of the cropped land falls, in the official instrument, in the two lowest classes. The mismatch has been documented in other mountain settings (Ceballos-Silva & López-Blanco, 2003), but class thresholds differ between studies and the figures are not comparable.

The mechanism behind the low classes of cropped land is not the one anticipated. On the declared parcels, the area-weighted mean slope coefficient is

0.73, and the area with a coefficient below 0.5 falls to 5.8%, against 18.0% on the modelled area. Slope remains the limiting factor on 54.9% of the declared area, precipitation on 31.8% and soil reaction on 23.9%; the percentages overlap because on 26.1% of the declared area the minimum coefficient is reached jointly by two or more factors. Cropped land is not flat, because the mechanisation threshold for ploughing is more permissive than the point at which the methodology begins to penalise slope, but its suitability class is pulled down by the same combination of factors, with less severe coefficients. The consequence for exposure assessment is direct: the exposure that the instrument attributes to the land and the exposure borne by the area actually cropped do not coincide, and the figure of 45.5% gives the order of magnitude of the gap between them, within the limits of a single season and a 30 m slope grid (Section 5.5).

4.4 Sensitivity and uncertainty

Scenario	Aggregation rule	Weights	Area changing class relative to sc. 3	Spearman's ρ	Weighted κ	Modal class (% of area)
1	Product (Eq. 1)	—	99.9%	0.968	0.096	III, 38.8%
2	Geometric mean (Eq. 2)	—	8.7%	0.968	0.747	I, 73.3%
3	Weighted sum (Eq. 3)	equal	reference	—	—	I, 77.0%
4	Weighted sum (Eq. 3)	Ceballos-Silva & López-Blanco (2003)	18.3%	0.731	0.175	I, 94.7%

Tab. 3. Sensitivity of the classification to the aggregation rule and the weight set. Agreement is reported against scenario 3, with equal weights.

The results of the four runs are given in Tab. 3. Replacing the product with the weighted sum moves 99.9% of the area into a higher class. The shift, however, is one of level, not of ranking. Expressed as a geometric mean so that it is on the same scale, the multiplicative index preserves the ranking of land units given by the equal-weight sum: Spearman's $\rho = 0.968$ and quadratically weighted $\kappa = 0.747$, with 91.3% of the area in the same class. Class agreement between the product and the sum is nevertheless close to nil, $\kappa = 0.096$, because the whole distribution moves. The two rules produce the same map with different thresholds — the same dissociation between class allocation and ranking of units that Keshavarzi et al. (2020) document on edaphic data.

Changing the weights, by contrast, re-ranks the land. The weights derived from Ceballos-Silva & López-Blanco (2003), calibrated in a high catchment in central Mexico, move 18.3% of the area, and agreement with the reference scenario drops to $\rho = 0.731$ and $\kappa = 0.175$, that is, slight agreement. A weight set published for the same crop and imported without recalibration does not preserve the classification of a mountain territory.

Instability is concentrated in the marginal class. Between the geometric mean and the equal-weight sum, class I remains the same across its entire area, class II remains the same over 82.7%, and class III changes entirely. The pattern reproduces the result obtained by perturbing the pairwise comparison matrix in a Xinjiang catchment, where instability was concentrated in the marginal classes (Li & Chen, 2020); that study assessed suitability for irrigation and is cited here for the pattern, not the object.

The divergence between rules follows the imbalance of the coefficient profile. The imbalance index, defined as the relative distance between the geometric and arithmetic means of a land unit's coefficients, averages 0.063 on the units that keep their class and 0.144 on those that change it. The rules part where a single factor dominates the profile and coincide where the coefficients are close to one another.

4.5 Narrative results

The seven households in the commune describe a shared trajectory of the cropped area. Five have reduced it, sometimes by an order of magnitude: “we had 10 hectares, 11 even. After that it all went down: to 7, 8, 6... until we got to one hectare” (I1). Only one household reports expansion, and it is the only one that combines three attributes: its own machinery, access to European funding and an active successor (I2). The contraction is described as affecting the whole commune: “the areas have gone down, maybe from the 100% they used to be, to some 30% of what was grown at one time” (I6). Withdrawal does not, however, take land off the register — “since 2007, when APIA came, there are subsidies on the land, and you have to work it” (I5) — and the gap between declared land and withdrawn crop bears on how the overlap in Section 4.3 is read.

Climatic hazard appears in the accounts as datable episodes, not as trends. The water deficit discussed in Section 4.1 is invoked most often. Alongside it come a cold, wet spring followed by failed emergence — “the potatoes sat in the ground a very long time, and they didn't come up” (I2) — and late blight associated with the combination of moisture and warmth (I1), while biotic pressures are described as increasing and linked to the thermal regime: “thirty years ago we didn't have to spray them for Colorado beetle, for blight. Now more and more” (I5).

The distribution of these accounts is itself a result: the thirty-one segments that document hazards and biotic pressures come exclusively from respondents in the commune and from the administration, whereas denial of a perceived change comes only from outside the commune (I9, I10).

Causal chains stated by respondents					
Biophysical origin					(7 chains)
drought at tuberisation	→	no irrigation	→	<i>reduced yield</i>	I1
cold, wet spring	→	failed emergence	→	<i>seed lost</i>	I2
moisture and warmth	→	late blight	→	<i>loss in the field</i>	I1
thermal change	→	biotic pressure	→	extra spraying	→ cost I5
stony soil	→	machinery wear	→	<i>cost</i>	I4
drier climate	→	unsuited cultivar	→	<i>cultivar dropped</i>	I2
rain at harvest	→	electric fence removed	→	wild boar damage	→ harvest lost I6
Economic or institutional origin					(9 chains)
imports, supermarkets	→	low price	→	lower income	→ contraction I2, I8
flat price, high cost	→	unprofitability	→	<i>contraction</i>	I6
no labour	→	land left unworked	→	<i>giving up</i>	I1
unworkable contracts	→	association dissolved	→	<i>no outlet</i>	I5
return clause	→	arrangement fails	→	<i>unsold produce</i>	I2
no cold storage	→	semi-early cultivars	→	<i>short sales window</i>	I2
seed unavailable	→	old cultivars lost	→	<i>uneven emergence</i>	I4, I6
subsidy on the land	→	land still worked	→	<i>crop withdrawn</i>	I5
origin label misused	→	<i>customers lost</i>			I1, I6

Each row reads from left to right; the final term, in italics, is the stated effect.

Fig. 4. Causal chains stated by respondents, grouped by the origin of the first term. Each row reads from left to right; the final term, in italics, is the stated effect. The argument comes from counting the rows: chains with an economic or institutional origin outnumber those with a biophysical origin, and two of the biophysical chains also end in an economic term.

The ranking of stated constraints departs from this picture. Asked openly what makes the difference between a good harvest and a poor one, five respondents name the weather and water first: “the weather comes first. If God doesn’t give water, there’s trouble” (I1). Taken together, the economic subcodes exceed this benchmark: the cost–price ratio appears in six interviews, market access in four, labour in three. Some respondents explicitly reverse the order: “first of all, not to depend on labour, because it’s hard to find” (I6). Unavailability of labour is given directly as the reason for withdrawal (I1). Soil, the criterion with the largest weight in suitability models, is invoked only by the administration and by growers from outside the commune (I9). The ranking

does not converge, and the divergence appears to vary with the farm's position (Tab. 4); with eight respondents, the pattern is described, not tested.

Resp.	First factors named at the open item	Mechanised	Stable market	Successor	Area trajectory
I1	Weather, drought; then blight and the beetle	no	no	no	10–11 ha → under 1 ha
I2	The market outlet, repeatedly	yes	yes	yes	expanding, about 5 ha
I3	The market outlet, sales, cost	—	no	yes	5 ha, stall shared by three families
I4	Weather, “it affects us 60%”; labour no longer matters	yes	—	—	5 ha → 3 ha → gave up
I5	—	—	—	—	under 1 ha
I6	Fertilisation, seed, land preparation	yes, since 2001	—	yes	3 ha, worked with his son
I7	Weather, wet year versus dry year	yes	yes, loyal customers	uncertain	3–4 ha → 2 ha
I8	Changing seed, changing land, irrigation	—	—	—	2 ha → 1 ha

Tab. 4. Ranking of factors stated at the open item, by respondent, alongside the state of the farm. The table is descriptive: no single rule links the first factor named to the state of the farm, and I2 names the market outlet although he reports a stable market. A dash marks a topic the interview did not touch, not an absent attribute; “uncertain” marks an answer that leaves the issue open.

The documented adaptation repertoire defines what is missing better than what is practised: mechanisation as a substitute for labour, rotation of cultivar and parcel (I7), organic fertilisation (I1), physical protection against wildlife, which has become a condition for growing the crop at all, “you can hardly plant potatoes any more unless you put up an electric fence” (I6), and semi-early cultivars, forced by the lack of temperature-controlled storage (I2). No grower in the commune irrigates. Irrigation appears in the commune’s corpus only as a condition growers lack (I8), and its absence is framed as resignation: “when there’s drought we don’t really have any solutions. [...] We leave it to fate” (I5). None of the documented practices acts on water deficit in the critical stage, the hazard named first, and the strategy actually most frequent becomes reducing exposure: “we’re giving up land because we can’t manage any more” (I4).

Marketing conditions come up in ten of the eleven interviews: the stall is shared by several families (I3, I8), prices are squeezed by imports and by organised retail (I2, I8), and unsold produce appears in five interviews.

The origin label is the subject of a recurring accusation of misuse — “they have papers saying they’re from Rîșca and they bring in produce from elsewhere” (I1) — with loss of customers as the stated consequence (I6). Direct observation provides the counterweight: of 58 stalls selling potatoes in eight markets, two displayed the origin, and none the cultivar, and a third “from Rîșca” sign was for beans. One grower nevertheless describes buyers’ recognition of the cultivar as current practice (I2). The information that growers regard as carrying value does not reach the point of sale in written form.

Collective action has been tried and has failed, in both cases over marketing. An association was dissolved after about three years because “contracts were needed that you couldn’t fulfil” (I5), and an earlier arrangement stopped at a clause on returning unsold produce (I2), compounded by the lack of storage and of mutual trust, “it’s as if everyone pulls for himself” (I2). Both episodes are old: the arrangement I2 describes worked “some ten years” ago. In 2022, five growers registered an agricultural cooperative whose main activity is growing roots and tubers in the commune, and in October 2026 it was presented as the first cooperative in the commune (TVR Cluj, 2026). Collective action has failed in the forms respondents experienced, and its recent revival lies outside the corpus.

Expectations for the future are anchored in demography, not climate. The absence of successors appears in five interviews, ageing in four: “people have got old, young families have either gone to town, or the older ones don’t plant at all any more” (I6). The conditions stated for keeping the crop, however, concern the market (I2). Decline is not a uniform experience. One respondent describes an improvement attributed to mechanisation, “back then we worked with the hoe, whereas now we work with the tractor” (I7). The divergence separates the same three attributes that set apart the only expanding household: mechanisation, a marketing channel and a successor.

4.6 Agreement between narrated parcels and modelled classes

Seven of the eleven respondents marked on the map the parcels they regard as their best, twelve sites in total. The sample is not probabilistic, so the results describe the parcels of these seven households, not the land considered good in the commune. Checked against the administrative source, 5 of the 12 sites fall inside a parcel declared under potato in the current season. Because the declared parcels were displayed during mapping, this overlap is not independent of the administrative source; the comparison with the model classes, which were not displayed, is. The other 7 are explained either by rotation, since a parcel in another year of the rotation appears under another crop code, or by imprecise location; the data do not separate the two causes. Since only the parcels declared under potato were displayed, a point placed outside all of them is less likely to be a misplaced marker than a choice of another parcel, which makes rotation the more probable of the two explanations without excluding imprecise location. The distinction between land that has left the crop and land in rotation can therefore be made only from the accounts.

The comparison was made against each class's share in the modelled area (Tab. 5). Eight sites fall in class III, where the expectation is 38.8%; three in class II, with an expectation of 6.2%; and one in class IV, where the expectation is 33.5%. None falls in the lowest class, which accounts for 21.4% of the modelled area. Eleven of the twelve sites are concentrated in the two

classes that together hold 45.0% of the area. Absence from the most suitable class carries no information: the model places 3.4 ha there, a thousandth of the modelled area, and the probability of hitting it is negligible by construction.

Point	Soil unit	Slope	Reaction	Soil volume	Humus	Precipitation	Class (Eq. 1)	Class (Eq. 3)	APIA potato parcel
P1	Typical subskeletal Eutricambosol	10	10	9	9	8	II	I	—
P3	Typical Districambosol	7	8	10	9	8	IV	I	yes
P4	Typical subskeletal Eutricambosol	10	10	9	9	9	II	I	yes
P5	Typical subskeletal Eutricambosol	9	10	9	9	8	III	I	yes
P6	Typical Districambosol	10	8	10	9	9	II	I	—
P7	Typical Districambosol	9	8	10	9	8	III	I	—
P8	Typical subskeletal Eutricambosol	9	10	9	9	8	III	I	—
P9	Typical Districambosol, moderately eroded	7	9	10	10	7	III	I	—
P10	Typical Districambosol, moderately eroded	7	9	10	10	7	III	I	yes
P11	Typical subskeletal Eutricambosol	9	10	9	9	8	III	I	—
P12	Typical Districambosol	9	8	10	9	8	III	I	yes
P13	Typical subskeletal Eutricambosol	9	10	9	9	8	III	I	—

Tab. 5. What the twelve sites indicated by respondents intersect. The indicator columns give the bonitation coefficient (1–10) of the polygon in which the point falls, not a measurement at the point; the value intervals and their coefficients are given in S3. The thermal coefficient is omitted because it is 10 at all twelve points. Point numbering follows the participatory mapping layer and does not correspond to the interview codes. The last column shows whether the point falls in a parcel declared under potato to APIA in the 2026 campaign.

The actual unit of analysis is not the site. With seven respondents as independent units, the deviations above are described, not tested. What can be said is descriptive: in this sample, the parcels named as good avoid the lower end of the official scale but do not cluster at its upper end.

The second comparison concerns criteria and does not depend on location. The criteria respondents invoke when describing a good parcel are slope, drainage, sun exposure and topographic position, the last with its mechanism made explicit, while texture is mentioned by the administration

representative and by the agronomist from outside the commune. Three of the model's criteria are named by nobody: soil reaction, soil volume and humus reserve. The last needs qualifying, because its absence is only apparent. Organic fertilisation appears in five segments and is described as a condition for yield, but as a household practice, not as a property of the land. The model measures a soil state; the respondent measures a management history.

The result above holds under the multiplicative rule. Under the other three rules, all twelve sites fall in the most suitable class, but the chance expectation for that class rises to 73.3% under the geometric mean, 77.0% under the equal-weight sum and 94.7% under the literature weights, which reduces the deviation to 26.7, 23.0 and 5.3 percentage points. Under the rule set in Section 3.7, agreement can be assessed only under a classification that separates the territory — here, the only one that does so is the multiplicative rule, the very rule that Section 4.2 shows to be the most severe.

5. DISCUSSION

5.1 Where the components converge, where they diverge and what the qualitative component corrects

Convergence between the two components was observed on one datable event, the drought of 2025 (Section 4.1); the frost that the series does not record marks a limit of the data. The convergence has a methodological consequence. A corpus of accounts can locate agronomically relevant events in an instrumental series without being able to establish a trend; the two uses must be kept apart.

Divergence occurs in two distinct places, with different status. The first concerns criteria: asked which is the best parcel, respondents name biophysical properties that the model contains; asked why the area has shrunk, they name operating cost, access, labour and the market, which it does not contain. The divergence arises because the questions differ. The second place is more serious, because it concerns what the instrument can represent: the last-frost date follows altitude with a correlation of 0.96, with no departure in the low valleys, whereas respondents describe differences in risk between topographic positions at the same altitude. The model does not contradict local observation; it is structurally unable to contain it.

Perception of climate change follows the respondent's position (Section 4.5), but the contrast admits two explanations that the data do not separate. One is positional: the contrast group lives in another pedoclimatic setting. The other is instrumental: the guide used in the markets contains fewer items on hazard. With two growers in the contrast group, the difference is described, not interpreted.

The economic diagnosis, on the other hand, converges across all categories. Falling sales, unsold produce and competition from cheap imports appear alike among growers from the commune, those from outside it and the trader. Where climate perception diverges by position, the assessment of market conditions does not.

A third relation adds to convergence and divergence. The qualitative component corrects two inferences that the spatial data alone would have supported, and the agreement protocol prevents a third. The 103.57 ha declared in the 2026 campaign would have passed as a measure of the crop that is maintained, although seven of the twelve sites named as good do not appear under the potato code; the data do not separate rotation from imprecise location (Section 4.6), but the accounts of rotation and of the obligation to work subsidised land show why the two do not overlap (Section 4.3). And the accounts of topographic position prompted a check of the climate field; its silence would have passed for absence of the phenomenon, although the fixed orographic lapse rate applied before interpolation makes the departure impossible to reproduce (Section 4.1). Better spatial data would reduce both corrections — a multi-year series of declarations, a climate field that represents inversions — but in this study it was the accounts that prompted both checks. The third concerns the comparison itself. Under three of the four rules, agreement with the indicated sites would have read as perfect, when chance expectation rises to 94.7% (Section 4.6); the indicated sites provide the test, but it is the correction for class shares that shows the test to be empty.

5.2 The ranking of constraints and what it means for multi-criteria weighting

The reasons for contraction given in the interviews are mostly not climatic: drought appears alongside labour and the market in one account (I1), and the properties of the land do not appear among them (Section 4.5). The claim rests on accounts, not on a measurement of withdrawal in space: the corpus only allows us to state that, when asked directly, growers do not name the land among the causes of contraction. The link between suitability and cropping decisions is also weak in the literature that measures it, with designs that do not transfer to an annual cash crop in Europe's mountains (Neswati et al., 2023; Cruz-Bello & Romero, 2025; Jaman et al., 2025).

Open elicitation of criteria produces two results with different status. One is a finding. Four of the constraints invoked do not appear in any of the official or published land suitability rankings we consulted: the parcel's manuring history, proximity to the homestead, wildlife pressure and the relation with the market. Criteria of this kind do, however, emerge under open elicitation in other settings too (Section 2.4). For the criteria they share, what differs is the weight each receives. The official methodology caps the location

penalty at 30% of the natural score and gives a parcel under 0.5 ha a coefficient of 0.90 and a dirt road also 0.90; respondents cite fragmentation and access among the reasons for leaving the crop. The instrument and the practitioners differ on the weight of each criterion, not on the list.

The divergence in weighting is not confined to the instrument and the practitioners; it runs through the literature itself, and the consequence is visible in our results: importing a weight set calibrated in another setting re-ranks the territory, with slight agreement relative to the reference scenario (Sections 3.3.3 and 4.4). The effect can go further than re-ranking. Under three of the four rules tested, the classification places more than 73% of the area in a single class, and under the imported weights the share rises to 94.7%. In these scenarios all twelve parcels indicated by growers fall in the most suitable class, with a deviation of 5.3 percentage points from chance expectation in the extreme case. Reported without correction for chance expectation, such a result would read as confirmation of the model, although a concentrated classification is all the harder to refute.

If the ordering of criteria varies with the state of the farm, weights derived from growers would also depend on who is asked; we did not run pairwise comparisons, so this remains a reasoned expectation, not a result. Indirect support comes from the divergence between experts' and farmers' weights reported for another potato cropping system (Rezaei et al., 2018).

5.3 Conditions of validity

The result on the thermal margin transfers to administrative units whose corrected mean annual temperature lies within 7.1–9.0 °C. Outside this range it ceases to hold: below the lower limit the constraint is of a different sign, and above the upper limit the climatic coefficient has already begun to fall. The condition can be checked from public data and is met here on 81.7% of the modelled area.

The other two results have different transfer conditions. Changing the aggregation rule affects any application of the official methodology, and thus the whole national territory, since the multiplicative rule and the scoring curves are the same everywhere; what varies from one territory to another is the size of the effect, which grows with the dispersion of the coefficients. The comparison procedure with grower-indicated parcels, however, requires two conditions that not every site meets: an exposure source independent of the model, and a tested classification that actually separates the territory, which does not happen under every weight set.

We expect the result to apply to a class of systems defined on two documented axes, a hypothesis for comparison rather than a finding of this study: agriculture-dependent mountain economies sensitive to climate change,

and regions of low adaptive capacity in central and eastern Europe (European Environment Agency, 2024). The commune lies on both.

5.4 Implications for risk management

The results concern the offices for pedological and agrochemical studies and those who use their surveys in decisions that involve risk. For the constraints that are properties of the land, the methodology does not need to be changed: the missing component is already provided for in it. The location bonitation layer has published coefficients for the land properties listed in Section 3.4, but it is not applied in spatial assessments because it requires data at cadastral parcel level. Parcel data now exist in the Land Parcel Identification System and in the systematic cadastre. The access component can also be addressed without cadastral geometry, as an accessibility analysis relative to settlements and markets.

The two hazards do not coincide in the series (Section 4.1), so the local response consists of two separate measures rather than a single plan for compound risk. The second recommendation concerns reporting. Agreement between a suitability map and current land use is, in current practice, reported as a percentage of overlap. Our results show that this percentage carries no information without the class shares in the reference territory, and that it becomes misleading under concentrated classifications. An assessment that does not state the chance expectation does not allow the reader to distinguish real agreement from agreement produced by class shares.

For local government and local action groups, the direct implication is that the factors invoked in withdrawal decisions are not represented in the instrument that underpins land-use decisions. At the European level, the uptake of adaptation measures is linked to generational renewal (Dentener et al., 2024), and the absence of successors appears in five interviews: a support policy built on land suitability does not reach this constraint.

5.5 Limitations and directions for further research

The limitations of the spatial model begin with the delimitation of the area, on which every percentage in Section 4 depends: the land cover product retains pasture and hay meadow alongside arable land, which inflates the low classes, since pasture occupies the steep slopes. Slope, which decides the classification on almost two thirds of the modelled area, comes from a 30 m elevation model and is underestimated in rugged relief, so the model overestimates suitability. The scoring curves were calibrated for an aggregation rule we do not use (Section 3.3.2), and without farm-level yields we cannot show which rule corresponds to attainable yield. The sensitivity analysis covers the change of rule and one weight scenario, not perturbation of each weight by $\pm 10\%$ and $\pm 20\%$. The topoclimatic correction of precipitation was not

calculated; the insolation steps used for the thermal correction come from forest ecology (Stanciu, 1981) and are applied without validation, and aspect was not kept as a layer, so its effect cannot be isolated. The climate indicators have limits of their own: a spell ends on any day with 1 mm or more, so days with 2–3 mm that do not relieve a drought split it into shorter spells, and daily air minima interpolated at about 1.5 km do not record ground frost or cold-air pooling (Section 4.1). The location layer was not calculated, compound events were not characterised with the metrics of the European framework, and the exposure source covers a single season.

The qualitative component has limitations of its own. The coding frame derives from the interview guide, so the ranking of factors rests only on the open item, and the accounts of blight are not records of *Phytophthora infestans*. Hazards are reported only by respondents from the commune, which may reflect different exposure or the shorter guide used in the markets. The support unit of the spatial comparison is the respondent, not the parcel, so deviations from chance expectation are described, not tested. The sample includes none of the five growers who set up the cooperative registered in 2022 (Section 4.5), so collective action appears only as an earlier failure, and the demographic outlook rests on growers who are withdrawing. Each market was visited on a single day. Above all, the assessment treats socio-economic vulnerability as static rather than as a process — the dominant practice in subnational climate risk assessments, and one criticised as such (Jurgilevich et al., 2017).

Three additions can be made on the existing data: systematic perturbation of the weights, reporting a range of stability; calculation of the location layer and of the topoclimatic precipitation correction, keeping aspect as a layer; and intersection of the indicated sites with the complete layer of single applications, the only operation that separates rotation from imprecise location (Section 4.6). Two others need new data: yields measured at farm level over several years on parcels of different classes, without which the choice of aggregation rule remains open for any application of the methodology, and a longer series or a regional pooling of similar communes to characterise compound events. On the social side, a corpus that includes the growers in the active cooperative would allow vulnerability to be treated as a process, with withdrawal and consolidation documented at the same time.

6. CONCLUSIONS

Applied to a mountain commune with six of its seventeen indicators, the official land evaluation instrument produces a verdict that rests mostly on a single criterion: slope decides the suitability class on almost two thirds of the modelled area, and under the multiplicative rule a single slope class reduces the score to one fifth, however favourable the other factors. The thermal component of the same instrument says something else. The potato optimum lies in the

submontane belt, four fifths of the modelled area sit on that optimum, and 5.2% have already passed it. Read as present aptitude, the index does not differentiate a mountain territory; read as the distance to a constraint, it becomes a risk indicator.

At this scale, the timing of a hazard matters as much as its magnitude. The longest dry spells in thirty-six years end before tuberisation, and the year one grower invokes is one of the two with a spell that falls within the window. The two hazards never coincide in the series, but the expected coincidence over thirty-six years is below half a year, so compound behaviour cannot be determined at this scale.

Comparing such a model with growers' judgement is informative only under a classification that separates the territory. Three of the four rules tested place more than seven tenths of the area in a single class, and agreement with the indicated parcels then becomes apparently perfect: a concentrated classification is less useful and harder to refute.

What growers name when they explain leaving the crop — operating cost, labour, succession and the market — is not in the model and cannot be added to it. Where they describe a land mechanism, the difference in frost risk between topographic positions at the same altitude, the model is structurally unable to contain it. Risk assessment needs both components: the model maps the exposure of the land, and the accounts name the constraints that decide whether the land is still worked.

Here the social component does not complement the spatial analysis; it corrects it on two points, each tied to a result and demonstrated in Section 5.1: the area declared each year does not measure the crop that is maintained, and the silence of the interpolated field on topographic position is not the absence of the phenomenon. A third point belongs to the protocol: agreement with a concentrated classification does not validate the model, and only a comparison judged against class shares shows it. Better spatial data would reduce both, but here it was the accounts that prompted the checks.

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Author contributions (CRediT)

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Conflict of interest

The authors declare no conflict of interest.

Data availability

The interview guides, the scoring tables by indicator, the aggregated results of the spatial analysis and the original Romanian wording of the quoted interview excerpts are available as supplementary material to this article (S1–S7). The spatial layer produced by the analysis, 6638 land units with the indicator values, the coefficients, the scores and classes of the four runs and the land cover class, is openly available as a feature service at https://services-eu1.arcgis.com/F8h2IR2H5gJFVO2V/arcgis/rest/services/Potato_land_suitability_classes/FeatureServer; its fields are described in S8. The parcels declared to the paying agency are not part of the published layer, which contains only the land units and their attributes. The interview transcripts cannot be shared: consent was obtained for use within this study, and the accounts contain location and household details that identify individuals in a small community of growers. The quotations used in the argument are given in full in the text, in English translation, with the respondent's code.

Declaration on the use of artificial intelligence

A generative artificial intelligence assistant (Claude, Anthropic) was used in preparing the manuscript, for the following tasks: drafting and rewriting the text in Romanian from the authors' own material — the interview transcripts, the attribute table produced by the GIS analysis and the bibliography compiled by the authors; rewriting the manuscript and the supplementary material in English from the authors' Romanian version, including the translation of the quoted interview excerpts; checking

bibliographic data, flagging attributions made through secondary sources and references that the check did not confirm; writing the scripts used to process the daily climate data in ArcGIS Pro and to extract the periods relevant for drought and cold, to compute area-weighted statistics from the attribute table, to build the file in the journal's format and to record changes as revision marks; drawing the diagrams in Fig. 2 and Fig. 4; and auditing consistency between in-text citations and the reference list, the numbering of tables and figures, and word counts. The authors also used Grammarly (Grammarly, Inc.) for language editing of the English text and reviewed each suggested change.

The assistant was not used to collect data, to conduct or transcribe interviews, to run the spatial analysis or to formulate the conclusions. The selection of indicators, the scoring curves and the coefficient values come from the official land evaluation methodology and from the authors' decisions; the assistant documented the scoring tables and flagged arithmetic inconsistencies, which the authors checked by recalculation.

The authors checked the statements, figures and references in the text, including the English version. The authors take full responsibility for the content. The tool does not meet the criteria for authorship and is not listed as an author.

Supplementary material

S1. Interview guide — growers in Rîșca commune. Six thematic blocks and the final mapping step, with items and probes. Referred to in Section 3.6.

S2. Interview guide — food markets. The two screening questions, categories A–D and the items specific to each category. Referred to in Section 3.6.

S3. Scoring tables by indicator. Value classes, methodology codes and potato coefficients for the six indicators in the model: S3.1 corrected mean annual temperature, S3.2 and S3.3 precipitation, for the two temperature ranges that determine which table applies, S3.4 slope, S3.5 soil reaction, S3.6 useful soil volume and S3.7 humus reserve. Referred to in Sections 3.3.1, 3.3.2 and 4.6.

S4. Dry spells by year, 1990–2025. Median across cells, extremes, dates of the median spell and number of cells on which a spell of at least ten days falls within the tuberisation window. Referred to in Section 4.1.

S5. Distribution of the modelled area over suitability classes, under the four aggregation rules, in both groupings provided by the methodology: five classes in steps of twenty points and ten classes in steps of ten points. Referred to in Sections 3.3.2 and 4.2.

S6. Reclassification tables for the thermal correction. Values assigned to the eight aspects (south 120, south-east 34, south-west 29, east and west 20, north-east and north-west 12, north 10) and to the ten slope classes (under 5°

50; 5–10° 45; 10–15° 40; 15–20° 35; 20–25° 30; 25–30° 23; 30–35° 20; 35–45° 15; 45–60° 10; over 60° 3), their product, and the six insolation–shading steps, with product intervals and percentage of normal insolation: over-insolated, above 1701, 90–100%; insolated, 430–1701, 70–90%; semi-insolated, 239–430, 50–70%; semi-shaded, 179–239, 30–50%; shaded, 101–179, 10–30%; over-shaded, below 101, 0–10%. After Stanciu (1981), in the form published by Tîrlă (2012). Referred to in Section 3.3.1.

S7. Original wording of the quoted interview excerpts. The Romanian text of every quotation used in the article, with the respondent's code and the section in which it is quoted. Referred to in Section 3.6 and in the data availability statement.

S8. Description of the published spatial layer. Address, coordinate system, the filter that defines the modelled area, and the content of each field. Referred to in the data availability statement.

S9. Methodological details moved from the main text. Coverage of the bonitation layer, indicators not retained, mapping of the literature weights, interview and observation procedures, the coding frame and the land cover excluded from the modelled area. Referred to in Sections 3.2, 3.3, 3.3.3, 3.6 and 4.2.

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