Climate Change Reshapes Vineyard Disease–Pest Pressure and Grape Yield Losses in Romania

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Abstract

Climate change is increasingly constraining Romanian viticulture by intensifying biotic stress and destabilizing grape yields. Across Europe, rising temperatures, altered precipitation seasonality, and more frequent extremes are reshaping grapevine–pest–pathogen interactions: downy and powdery mildews remain dominant phytosanitary threats, while chronic decline syndromes linked to grapevine trunk diseases and the spread of invasive organisms expand risk profiles and management costs. In Romania, producer reports and surveillance outputs consistently highlight recurrent pressure from Plasmopara viticola (downy mildew), Erysiphe (Uncinula) necator (powdery mildew), Botrytis cinerea (bunch rot), Pseudopeziza spp., and key pests including Lobesia botrana and eriophyid mites (Eriophyes/Colomerus spp.), with implications for yield stability and intervention intensity. Here we propose a reproducible, country-level framework for Romania (2015–2025) that integrates three open-data pillars: (i) official crop statistics for grape production and yield (INSSE/TEMPO and harmonized EU reporting), (ii) publicly posted phytosanitary warning bulletins as an operational proxy for disease–pest pressure, and (iii) reanalysis-based climate descriptors suitable for viticulture risk assessment. A national Warning-Bulletin Pressure Index (WBPI) is constructed by systematically collecting, filtering to vineyard-relevant advisories, removing duplicates, and aggregating annual counts by territory; where possible, WBPI is also normalized to account for reporting effort (e.g., bulletins per issuing unit/year) and tested for sensitivity to changes in bulletin volume. Climate covariates are derived from ERA5-Land/ERA5 products using standardized growing-season indicators aligned with vine phenology (e.g., heat accumulation, hot-day frequency, and precipitation regime metrics including seasonal totals and dry-spell structure), spatially aggregated to the territorial scale used in statistical reporting. We outline an attribution strategy that links interannual production and yield anomalies to climate and WBPI signals using trend–cycle decomposition and regression models with lagged sensitivity windows, emphasizing interpretability for risk management rather than purely predictive skill. As an empirical anchor, official series indicate that Romania reached approximately 1,069 kt of grapes for wine in 2018 and declined to ~668 kt by 2024 (≈37.5% contraction), underscoring the magnitude of recent volatility and motivating integrated climate-biotic assessments. The resulting pipeline supports rapid annual updates as new statistics and bulletins become available and provides actionable evidence for adaptation planning (cultivar/clone choice, canopy and irrigation strategy, forecast-informed spray timing, and integrated pest management), while explicitly recognizing that warning bulletins capture both biological pressure and surveillance/reporting intensity.

Keywords: *viticulture; Romania; yield variability; climate change; downy mildew; powdery mildew; Lobesia botrana*

1. Introduction

Modern viticulture is increasingly defined by a convergence of pressures in which climate change is not simply an external stressor but a primary force reshaping the epidemiological landscape of vineyards. Shifting climatic parameters-expressed through warming, altered precipitation regimes, and more frequent or more intense extremes-interact directly with the biology of pathogens and pests, producing a biotic environment that is both more dynamic and, for grapevine cultivation, progressively more hostile [1-3]. Romanian vineyards are embedded within a continental climate setting that is rapidly warming and experiencing precipitation change, and this positioning makes them particularly exposed to climate-driven escalation of biotic risks involving key fungal diseases, oomycete pathogens, insect pests, and chronic wood-degrading syndromes [1,3]. In this context, the major biotic constraints that already structure vineyard protection - *Plasmopara viticola, Erysiphe necator, Botrytis cinerea, Pseudopeziza* spp., *Lobesia botrana*, eriophyid mites, and grapevine trunk diseases (GTDs) such as Esca, Eutypa dieback, and *Phomopsis dieback*-become especially consequential because their population dynamics, infection biology, and damage expression are all sensitive to the climatic trajectories currently observed across Central and Eastern Europe [1-3].

A central vulnerability underlying this intensification is the biological legacy of grape domestication and dissemination: the vast majority of commercially cultivated grapevines belong to Vitis vinifera, a species described as carrying no endogenous resistance genes against its most damaging pathogens, *E. necator* and *P. viticola*, both originating in North America and introduced to Europe in the nineteenth century [4,5]. This baseline susceptibility is not an abstract genetic limitation; it sets the stage for climate sensitivity because both pathogens are polycyclic and capable of rapid epidemic amplification when environmental thresholds are met [2,6]. Consequently, even relatively small shifts in temperature, humidity, and precipitation regimes can translate into disproportionately large changes in disease pressure, requiring tighter protection schedules and increasing the probability of yield and quality losses when protective coverage is imperfect or weather-driven infection windows outpace management [2,6]. These constraints make Romanian viticulture a particularly informative case for examining how climate change converts climatic variability into measurable

biotic risk through mechanistic pathways that operate at the scale of pathogen and pest life cycles, host phenology, and management feedbacks [1–3].

Climate change amplifies vineyard biotic risk through multiple, often synergistic mechanisms. Rising mean temperatures, altered precipitation patterns, increased frequency of extreme events, and shifts in seasonal phenology jointly modify infection biology, epidemiology, and population dynamics across grapevine pathogens and pests [1–3]. Temperature exerts a direct control on developmental rates and survival for many organisms affecting vineyards, but its effects are most clearly expressed when coupled to moisture, leaf wetness, humidity, and the timing of susceptible host tissues. For *E. necator* (powdery mildew), development is described as explicitly favored by increases in average summer temperatures, and intensification has been linked to conditions characterized by prolonged high temperatures, high atmospheric humidity, and reduced rainfall [2]. The same climatic directionality also influences winter survival and early-season inoculum formation, such that milder winters can enhance overwintering success and accelerate epidemic onset, effectively compressing the time available for preventive intervention while increasing the likelihood that early infections seed larger secondary cycles later in the season [2]. This matters for Romania because changing seasonal profiles can adjust not only the magnitude of risk but also its timing relative to canopy development and the period during which infections most strongly constrain yield formation.

For *P. viticola* (downy mildew), the climate linkage is mechanistically different but no less consequential because infection depends on specific combinations of leaf wetness and warm temperature that enable zoospore-mediated entry through stomata [7,8]. *P. viticola* is described as an obligate biotroph oomycete that infects green tissues—leaves, tendrils, bunches, shoots—producing characteristic green-yellow "oil spot" lesions on leaves and brown symptoms on bunches with a dramatic decrease in grape quantity and quality [7,8]. Zoospores are released either from primary sporangia produced from overwintered oospores or from sporangia derived from sporulating oil spots, enabling both primary and secondary infection cycles [8]. The polycyclic nature of the pathogen, alternating sexual and asexual cycles that both lead to zoospore production, implies that climate-driven increases in the frequency of warm, humid periods can create episodic but highly favorable infection windows that initiate and sustain rapid epidemic development [6]. Downy mildew epidemics are described as frequent and capable of serious yield losses, making this disease a primary sanitary concern for vineyard owners in Europe [6]. In practice, the disease remains largely controlled by fungicide applications because efficient preventive agronomic practices are characterized as still lacking; in France, anti-downy mildew fungicides are noted as accounting for approximately 40% of total phytosanitary treatments on average, illustrating how strongly disease risk can structure chemical input intensity under European conditions [6].

These direct climatic effects on pathogen biology translate into broader systemic consequences for vineyard management. Climate change is described as shifting pathogen distribution and dynamics, demanding more intense plant protection in some regions and thereby increasing viticulture's dependence on phytochemicals and pesticides [3]. This dependency is not neutral: increasing chemical input intensity raises selection pressure for fungicide resistance, producing a feedback loop in which climate-enhanced disease pressure prompts more treatments, and more treatments accelerate resistance evolution, which then further complicates disease control [3,9,10]. Resistance dynamics are explicitly relevant for both downy and powdery mildew. QoI resistance associated with the G143A mutation has been detected in isolates of *P. viticola* and *E. necator*, and in Europe QoI resistance in grape downy mildew was first observed in 2000 and has since become common in many grape-growing areas [9]. In parallel, resistance to multiple fungicide classes in E. necator is described as widespread, making fungicidal suppression especially problematic and increasing the practical cost and strategic complexity of maintaining control across seasons marked by favorable climatic conditions [10,13]. These management constraints are particularly consequential in a production system dominated by *V. vinifera* susceptibility and characterized by repeated annual fungicide programs; the propensity of *E. necator* to develop resistance within a few years after widespread fungicide deployment is specifically highlighted as one driver of interest in alternative control strategies [10].

Climate change also operates through redistribution and emergence pathways. In the aftermath of global climate change, new emerging diseases are described as becoming epidemic in viticulture, including Black Rot (*Guignardia bidwellii*) and GTDs [1]. Warming can render previously cooler regions suitable for organisms historically limited by temperature, while simultaneously stressing vines in ways that reduce constitutive and induced defenses, creating conditions in which both established and emerging threats gain epidemiological traction [1,3]. This theme extends from pathogens to pests. L. botrana (European grapevine moth) is described as multivoltine-completing two to four generations per year depending on temperature-with first-generation larvae feeding on flower clusters and subsequent generations feeding on and within berries [11]. Because development and voltinism are temperature-dependent, warming is expected to increase generation number and facilitate geographic expansion into previously unsuitable areas [11]. Eriophyid mites, including *Colomerus vitis* (grape erineum mite) and *Calepitrimerus vitis* (grape rust mite), are likewise integrated into vineyard risk because they cause symptoms such as erineum galls, shoot distortion, and reduced photosynthetic capacity, and they benefit from warm, dry conditions that accelerate reproduction and can reduce the effectiveness of natural enemies and fungal entomopathogens [11,12]. When these pest pressures are superimposed on climate-driven disease intensification, risk becomes multidimensional: vines experience simultaneous tissue loss, reduced functional canopy, altered source–sink relations, and increased infection entry points.

A further layer of complexity arises from the tight coupling of pathogen success to grapevine phenology and tissue susceptibility. For downy mildew, disease development in bunches is described as strongly dependent on phenological stage: inoculation during early stages can produce visible symptoms in susceptible cultivars, with inflorescence swelling inoculations causing desiccation of the inflorescence and end-of-flowering inoculations producing partial bunch desiccation; after inoculation of pea-sized berries, brown rot symptoms appear, whereas infections are not observed after inoculation at veraison as stomata lose function and infection severity is reduced [8]. Histological and molecular observations described for bunch infection indicate invasion of most bunch tissues while emphasizing stomata as the infection site and noting that mycelium and haustoria are never observed in vascular tissues [8]. These phenology-dependent dynamics matter under climate change because climatic shifts can change the alignment between infection-favorable weather and vulnerable phenological windows, thereby altering both epidemic timing and the most damaging infection events. They also interact with decision support systems (DSS) and forecasting models that depend on historically calibrated relationships between weather and phenology. Primary infection timing is described as being influenced by temperature and moisture conditions, and DSS such as VitiMeteo-Plasmopara and Agrométéo have been developed to predict primary infection timing based on meteorological data to optimize fungicide application timing [14,11]. However, climate change is described as altering phenological relationships underpinning these models, potentially reducing predictive accuracy and necessitating continuous

recalibration, a requirement that becomes more urgent as the cost of mistimed protection increases in seasons with rapid epidemic acceleration [11].

The Romanian context amplifies the importance of these mechanistic considerations because continental conditions can produce episodic but intense infection periods and because management decisions must accommodate variability across a range of altitudes and climatic zones. Downy mildew is described as capable of causing complete yield loss in unprotected vineyards, especially in humid wine regions where significant fungicide use is necessary to maintain plant health [5]. The pathogen's capacity to infect all green tissues, combined with rapid asexual cycling, implies that even brief lapses in protective coverage during favorable weather can result in catastrophic crop losses [7,6]. Powdery mildew is likewise described as causing severe yield and quality losses without intensive fungicide use and as being widely regarded among the most destructive grape pathogens worldwide [10]. Under warming and rain-reduction conditions described as favorable for *E. necator*, the relative balance between mildew diseases can shift because powdery mildew can infect under comparatively drier conditions, whereas downy mildew requires free water for zoospore release and infection [2,13]. This contrast implies that Romanian vineyards experiencing warmer, drier summers may confront not a simple uniform increase in disease pressure but a reweighted disease complex, with direct implications for monitoring intensity, treatment selection, and the logic of integrated protection programs [2,13].

At the molecular and population levels, pathogen–host interactions provide additional mechanisms through which climate-mediated pressure can translate into management difficulty. For *P. viticola*, the absence of evolutionary defense mechanisms in V. vinifera is linked to the pathogen's North American origin and nineteenth-century introduction to Europe [5]. The pathogen is described as employing effectors to suppress host immunity and manipulate host responses early in infection; in compatible interactions, more than 57.2% of differentiated transcripts from infected leaves were down-regulated at 24 hours post-inoculation, consistent with active manipulation of host responses [15]. For *E. necator*, population structure is described as including two distinct genetic groups (A and B) with different ecological requirements and differing fungicide sensitivities, a feature that directly informs resistance management and epidemiological interpretation under changing climatic conditions [15]. In compatible interactions with *E. necator*, 90% of differentiated transcripts were down-regulated at 24 hours post-inoculation, and benzothiadiazole (BTH) treatment is described as enhancing defenses, inhibiting pathogen growth (61–98% depending on isolate) and triggering up-regulation of pathogenesis-related genes including PR-3, PR-6, and PR-10 [15]. These mechanistic details underscore that climate-driven increases in infection opportunity operate against a background in which pathogens can suppress or evade host responses and in which populations differ in ecological performance and fungicide sensitivity, thereby shaping epidemic behavior and control outcomes.

Genetic resistance breeding and biotechnology are positioned within this landscape as responses to susceptibility and resistance erosion, but they are themselves constrained by pathogen adaptation. Resistance loci against downy mildew are described as including Rpv loci such as Rpv1 from *Muscadinia rotundifolia*, Rpv3 from American *Vitis* species (present in cultivars such as Regent, Bianca, Villard blanc), and Rpv10, characterized through QTL mapping and marker-assisted selection [4,16–18]. Powdery mildew resistance loci are described as including Run1 from *M. rotundifolia* (blocking development at early stages), Ren1 from *Vitis romanetii*, Ren3 from Regent, and Ren9, with epistatic interactions noted where combining Run1 with QTLRgP does not increase resistance beyond Run1 alone [4,17,18]. Yet the durability of resistance is described as threatened: the Rpv3.1 factor in cultivars such as Bianca and Regent has been overcome by virulent *P. viticola* strains, and E. necator strains from V. rotundifolia can break total resistance conferred by Run1 [12]. Climate change is implicated as a driver that can increase selection pressure and facilitate population mixing through altered dispersal patterns, accelerating virulence evolution and undermining resistance-based control strategies [12]. In parallel, biotechnological approaches described for *E. necator*-including CRISPR/Cas9 editing of susceptibility genes such as VvMLO3 and VvEDR1 and RNA interference targeting VvMLO6/7/11 illustrate attempts to engineer durable resistance within V. vinifera backgrounds that otherwise lack endogenous resistance [1]. These approaches become particularly salient in a climate context that intensifies disease pressure and amplifies the costs of resistance breakdown or partial resistance erosion [1,12].

Beyond the mildew pathosystems, the Romanian vineyard biotic complex includes pathogens and pests whose interactions can amplify losses. *B. cinerea* (grey mold) is described as one of the three most important grapevine diseases alongside powdery and downy mildew, and it is characterized as a necrotroph capable of saprophytic persistence, primarily damaging berries and causing significant losses in yield and wine quality [1,19]. The disease is associated with cool, humid conditions favorable for sporulation and infection, while also exploiting wounds and physiological stress caused by other pathogens or abiotic factors [19]. Importantly, *B. cinerea* is described as co-occurring within multiplex detection systems alongside *P. viticola* and *E. necator*, reflecting how protection programs operationally manage these threats as an integrated complex rather than as isolated problems [14]. This integration becomes more critical under climate change because pest–pathogen synergy can convert incremental pest damage into disproportionate disease and yield impacts. *L. botrana* larval feeding directly damages berries and is explicitly linked to secondary infection by *B. cinerea* and other pathogens, creating a synergistic interaction between pest and disease pressure [11]. Climate warming that increases moth voltinism simultaneously increases the frequency of berry injury events and can create conditions conducive to increased grey mold pressure on wounded berries, thereby amplifying yield losses beyond what would be expected from either organism acting alone [1,11]. Eriophyid mite feeding damage, by reducing photosynthetic capacity and interacting with vine stress, can further reduce tolerance to other biotic and abiotic pressures, contributing to cascading effects on vine health and productivity under warmer, drier conditions [11,12].

These interacting pressures-susceptible host genetics, climate-mediated shifts in infection opportunity and population dynamics, escalating pesticide dependence with resistance feedbacks, phenology-dependent vulnerability, and multi-stressor synergy-define the contemporary challenge space for Romanian viticulture. They also frame the need for management strategies that can maintain effective control while reducing reliance on synthetic fungicides, a need explicitly linked to climate-driven escalation of biotic risk and its chemical-management consequences [1,3]. The search for such strategies is illustrated by approaches described for powdery mildew suppression using germicidal UV-C light, which has also demonstrated activity against downy mildew, the sour rot complex, and mites, suggesting the possibility of integrated methods that simultaneously address multiple threats present within vineyard systems [13]. Similarly, for *B. cinerea*, natural compounds derived from V. vinifera canes, including ε-viniferin, have demonstrated antifungal activity, indicating potential for developing novel natural fungicides from viticulture waste material and aligning disease control innovation with broader sustainability objectives [19]. Within a Romanian setting where climate change is intensifying or reconfiguring the biotic risk complex, such mechanistically grounded and system-aware approaches are positioned as responses to a problem that is simultaneously biological, climatic, and management-structural in its determinants [1–3,9,13,19].

2. Matherial and method

This study was designed as a county-level assessment of climate–biotic pressure linkages in Romanian viticulture over 2014-2024. The study area was defined by selecting the ten counties that jointly represent Romania's largest vineyard cultivated areas and highest grape output (harvest) over the study window: Vrancea, Vaslui, Iași, Dolj, Buzău, Prahova, Constanța, Tulcea, Alba, and Arad. Viticultural statistics were retrieved from INSSE TEMPO-Online [20]. County selection was operationalized using a composite ranking based on two official county-level indicators computed for each year and then summarized across the study period: (i) vineyard cultivated area (ha) and (ii) grape production relative to cultivated area (t), where output was calculated as area (ha) × yield ($t \cdot ha^{-1}$). For each county, ranks were computed for the multi-year mean area and the multi-year mean output (2014–2024), and the two ranks were combined (summed) to identify the top-10 counties, ensuring that inclusion reflects both structural vineyard extent and production relevance rather than area alone.

Viticultural indicators were compiled annually for each county (2014–2024), including vineyard cultivated area (ha) and grape yield, standardized to $t \cdot ha^{-1}$ (values reported in $kg \cdot ha^{-1}$ were converted to $t \cdot ha^{-1}$). Climate exposure was characterized using a dual approach. First, daily climate series were extracted at county-seat proxy points using the Open-Meteo historical endpoint, retrieving daily mean air temperature (°C) and daily precipitation totals (mm); these were aggregated into annual indicators and growing-season (April–October) indicators (mean temperature; precipitation sum). Second, climate was cross-checked using ERA5/ERA5-Land reanalysis [21,22] accessed via the Copernicus Climate Data Store [23], sampled as county-scale spatial averages for the corresponding variables (2 m air temperature and total precipitation), converted to °C and mm, and summarized into the same annual and April - October metrics to provide a spatially consistent benchmark.

Biotic pressure was characterized using phytosanitary warnings compiled from two official information streams for 2014–2024: the ANFDF bulletin archive (https://old.anfdf.ro/teritoriu/buletine.html) and county-level advisories posted by the County Directorates for Agriculture. Warnings were filtered to retain items explicitly relevant to grapevine/vineyards, structured by publication date, county, and target organism(s), and coded into standardized categories to enable consistent aggregation through time, emphasizing downy mildew (*Plasmopara viticola*), powdery mildew (*Erysiphe/Uncinula necator*), European grapevine moth (*Lobesia botrana*), and mites (eriophyid mites such as *Eriophyes*/*Colomerus* spp., as reported). When a single warning referenced multiple targets, each target was recorded to allow organism-specific annual counts while retaining warning-level context. Because warnings are advisories rather than direct field incidence measurements, warning frequency was interpreted as a proxy of perceived phytosanitary pressure and standardized through consistent filtering and coding across counties and years.

All variables: vineyard area (ha), yield ($t \cdot ha^{-1}$), Open-Meteo climate indicators (°C; mm), ERA5 county-average indicators (°C; mm), and warning-derived indices ($counts \cdot year^{-1}$) were merged into a unified county–year panel to support temporal characterization, cross-county contrasts, stratified summaries, and evaluation of climate – warning - productivity relationships over 2014–2024. Data processing and figure generation were performed in Python [24] using pandas [25], NumPy [26] and Matplotlib [27].

3. Results and Discussion

Using INSSE/TEMPO county-level series (2014–2024) for on-bearing vineyard area (ha) and grape yield ($kg\ ha^{-1}$), we characterised productivity as yield for 10 major vineyard counties (Vrancea, Vaslui, Dolj, Buzău, Constanța, Prahova, Tulcea, Alba, Iași, Arad) (Fig. 1). Across 110 county-year observations, yield ranged from 2,722 $kg\ ha^{-1}$ (Dolj, 2016) to 8,998 $kg\ ha^{-1}$ (Alba, 2019), indicating substantial interannual variability at county level. The cross-county mean yield reached its minimum in 2016 (4,352 $kg\ ha^{-1}$), rebounded sharply in 2017–2018 (peak mean yield in 2018: 7,062 $kg\ ha^{-1}$), declined in 2019 (6,061 $kg\ ha^{-1}$), recovered in 2021 (6,842 $kg\ ha^{-1}$), and deteriorated again in 2022–2024, reaching 4,590 $kg\ ha^{-1}$ in 2024.

Variability was quantified using the coefficient of variation ($CV = \sigma/\mu$, computed over 2014–2024). The most variable counties were Dolj (CV ≈ 0.280), Arad (≈0.244), Prahova (≈0.215), and Constanța (≈0.199), reflecting either large single-year shocks (e.g., Constanța 2017) or sustained late-period declines (e.g., Arad and Prahova toward 2024) (Fig. 2). "Shock years" were identified from the county-median year-to-year yield change: 2017 represents the strongest synchronised rebound (10/10 counties increased; median $\Delta \approx +1{,}930\ kg\ ha^{-1}$), whereas 2022 marks the strongest contraction (9/10 counties decreased; median $\Delta \approx -1{,}546.5\ kg\ ha^{-1}$). Notably, vineyard area across these 10 counties changed only modestly in aggregate (≈ −1.8% from 2014 to 2024), implying that the observed production instability is driven primarily by per-hectare productivity fluctuations rather than large changes in on-bearing area.

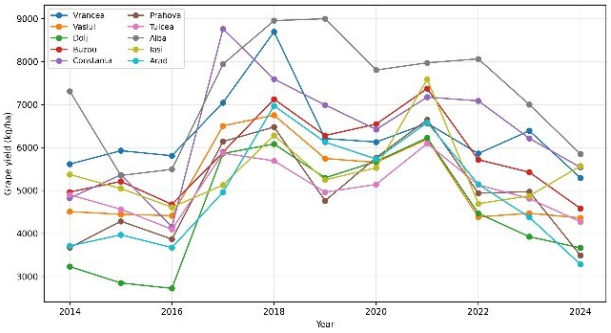

Fig. 1. Grape production relative to cultivated area 2014-2024

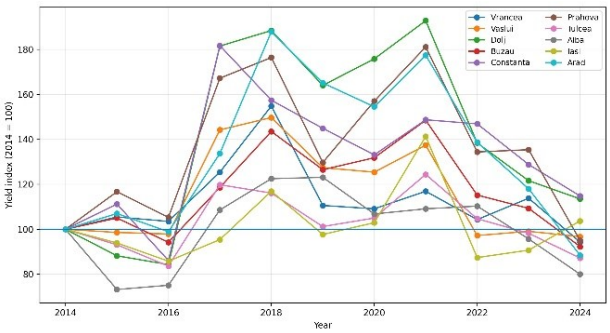

Fig. 2. Relative change in yield by county 2014-2024

County-scale linear tendencies derived from ERA5-based annual series (2014 - 2024) reveal a spatially coherent warming signal across all 10 study counties, with short-window rates of approximately ~0.75 - 1.70 °C per decade (Fig. 3). Warming is strongest in Dolj (~1.7 °C/decade) and remains elevated in Buzău, Vrancea and Prahova (≈1.4 - 1.5 °C/decade), while Alba and Arad show the weakest increases (~0.75 - 0.80 °C/decade).

In contrast, precipitation (Fig. 4) exhibits predominantly negative tendencies, indicating an emerging drying signal with substantial spatial heterogeneity: the largest declines are inferred for Prahova (~ -280 mm/decade) and Buzău (~ -240 mm/decade), followed by Dolj (~ -220 mm/decade) and Vrancea/Constanța (~ -180 mm/decade), whereas Iași (~ -55 mm/decade) and Vaslui (~ -20 mm/decade) show comparatively weak drying and Alba is near-neutral to slightly positive. Interpreted jointly, the co-occurrence

of faster warming and stronger drying in Prahova-Buzău-DoljVrancea-Constanța defines an aridity-prone subset of counties that overlaps with pronounced yield instability observed in the INSSE series (2014 - 2024), including the broad contraction in productivity after 2021. These hydroclimatic tendencies are consistent with a shift toward higher frequency of heat- and water-limitation years, providing a plausible climatic backdrop for the late-period yield weakening and the elevated phytosanitary warning intensity (WBPI) documented in the same counties.

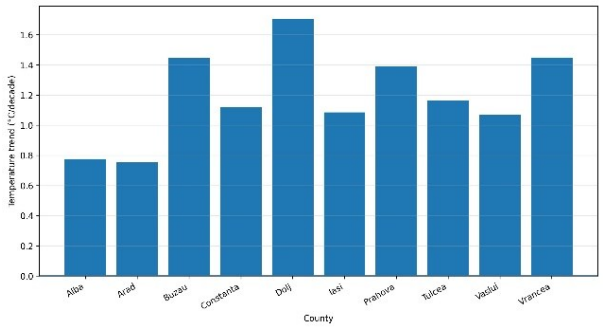

Fig. 3. Temperature trend by county 2014-2024

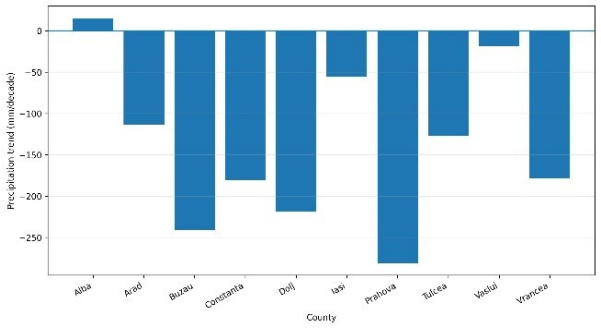

Fig. 4. Precipitation trend by county 2014-2024

Tab. 1 Frequency of official warning bulletins as a proxy for pest and pathogen incidence in Romanian vineyards: county-level patterns, 2014–2024

Agent/species	Vrancea	Vaslui	Dolj	Buzău	Constanța	Prahova	Tulcea	Alba	Iași	Arad
Fungal diseases										
Total (category)	**29**	**35**	**138**	**118**	**22**	**74**	**7**	**76**	**16**	**21**
Erysiphe necator	12	17	52	42	11	29	3	30	4	12
Plasmopara viticola	14	13	44	34	11	24	4	25	10	9
Botrytis cinerea (incl. Sclerotinia/B. fuckeliana)	3	5	30	22	0	11	0	8	2	0
Gloeosporium ampelophagum	0	0	10	20	0	10	0	10	0	0
Guignardia bidwelli	0	0	0	0	0	0	0	3	0	0
Insect pests										
Total (category)	**14**	**24**	**31**	**47**	**9**	**28**	**1**	**27**	**0**	**3**
Lobesia botrana	4	11	24	36	9	21	1	20	0	3
Thrips tabaci	1	0	7	11	0	7	0	7	0	0
Eupoecilia ambiguella	1	11	0	0	0	0	0	0	0	0
Scaphoideus titanus	6	1	0	0	0	0	0	0	0	0
Empoasca vitis	2	1	0	0	0	0	0	0	0	0
Mites										
Total (category)	**8**	**24**	**49**	**39**	**7**	**22**	**4**	**25**	**0**	**12**
Tetranychus urticae	2	14	49	39	7	22	4	22	0	0
Eriophyes vitis	6	10	0	0	0	0	0	3	0	12
Others										
Total (category)	**2**	**0**	**0**	**2**	**0**	**0**	**0**	**0**	**0**	**0**
Arion vulgaris	2	0	0	2	0	0	0	0	0	0

[a] Note: Values represent the number of warning signals recorded in phytosanitary bulletins (frequency-based proxy), not field-measured incidence (%).

Table 1 summarizes a bulletin-derived "warning frequency" proxy for vineyard biotic pressure across 10 Romanian counties over 2014–2024 (counts of warning signals, not field-measured incidence). Overall, signals are highly concentrated in a few counties: Dolj (218) and Buzău (206) dominate, followed by Alba (128) and Prahova (124), whereas Tulcea (12), Iași (16), Arad (36) and Constanța (38) show comparatively low reporting intensity. This heterogeneity likely reflects both underlying risk and differences in local surveillance, advisory activity, and viticultural structure. Across all counties, fungal diseases are the leading category, contributing ~51–63% of total signals in most locations (e.g., Dolj 138/218; Buzău 118/206; Alba 76/128; Prahova 74/124), and 100% in Iași within this extracted log.

Fungal diseases dominate the warning burden (537/927 ≈ 58%), followed by mites (198/927 ≈ 21%) and insect pests (187/927 ≈ 20%). Other agents are negligible (<1%). Spatially, warning intensity is highly concentrated: Dolj (218) and Buzău (207) account for nearly half of all logged signals, followed by Alba (128) and Prahova (124). Tulcea (14) and Iași (16) exhibit very low totals. These differences likely reflect both true agronomic pressure and variation in reporting intensity across territorial units.

Agent-level structure is anchored by *Plasmopara viticola* and *Erysiphe necator* (mildews), *Lobesia botrana* (grape moth), and *Tetranychus urticae* (mites), which together structure the warning landscape in high-signal counties.

4. Integrated Analysis of Bulletin-Derived Biotic Risk, Climate, and Grape Yield (Romania, 2014–2024)

Across the 10 study counties, the joint climate-biotic-production signal over 2014-2024 is best described as rapid warming, -highly variable precipitation with an overall tendency toward drying in most locations, and -increasingly unstable grape yields, with a pronounced late-period deterioration (2022-2024). Importantly, the bulletin dataset represents a warning-frequency proxy (advisory intensity) rather than field-survey incidence; therefore, it captures a combined effect of biological pressure, weather-triggered risk, and institutional reporting effort.

All counties exhibit positive temperature trends over the period, ranging from ~+0.75 to +1.71 °C per decade (lowest in Arad/Alba; highest in Dolj, followed by Vrancea and Buzău). Precipitation shows strong interannual variability and predominantly negative linear trends (up to roughly −280 mm per decade in Prahova; also markedly negative in Buzău and Dolj), with Alba as the notable exception (near-flat to slightly positive). At the multi-county scale, 2021 is the coolest year, 2024 the warmest, while 2022 stands out as the driest year—an important candidate "stress year" for viticulture because it combines elevated thermal load with reduced water availability.

Yields (kg/ha) show large county-scale variability, with the decade's lowest mean occurring in 2016, a widespread rebound in 2017-2018 (peak mean in 2018), and a clear weakening after 2021. The late-period decline is consistent across all counties: 2024 yields are lower than 2021 in every county, with the largest drops in Arad (-3.30 t/ha), Prahova (-3.16 t/ha), Buzău (-2.79 t/ha), and Dolj (-2.56 t/ha). This pattern is mechanistically plausible given the combination of warming, precipitation deficits (especially 2022), and the cumulative effects of chronic stress on canopy function and berry filling.

The warning proxy totals 927 vineyard-relevant signals across the decade, but it is strongly concentrated in Dolj (218) and Buzău (207), followed by Alba (128) and Prahova (124). Compositionally, the warning spectrum is dominated by fungal disease advisories and the canonical vineyard complex:

- Powdery mildew (*Erysiphe necator*) is the single strongest signal (125 total),
- mites (primarily *Tetranychus urticae*) are similarly high (122),
- downy mildew (*Plasmopara viticola*) remains central (115),
- grape moth (*Lobesia botrana*) forms the core insect-pest signal (65),with grey mould (*Botrytis cinerea*) and several "other" agents contributing secondarily.

Two robust integrative observations emerge:

1. Counties with the highest bulletin pressure tend to have more unstable yields. At county scale, cumulative warning burden is moderately aligned with yield volatility (e.g., Dolj combines the highest warning totals with the highest yield dispersion; Prahova and Arad also show high variability). This is not a one-to-one relationship - Constanța has relatively low total warnings but high yield range-underscoring that bulletin intensity is not a pure biological metric.
2. The timing of peak warning years aligns with the late-period climate stress regime. Peak warning pressure clusters in 2022 (notably in Dolj and Buzău) and 2024 (Vaslui, Vrancea, Prahova), years that also correspond to extreme hydroclimatic conditions (2022 drought and 2024 exceptional warmth) and to the observed yield downturn. This supports a coherent narrative in which warming raises baseline risk, while episodic precipitation deficits and heat amplify vulnerability-both by direct physiological stress and by shifting pest–pathogen dynamics, increasing the need for (and frequency of) advisory interventions.

5. Conclusion

This study develops and applies a reproducible, county-scale framework to examine how recent hydroclimatic conditions and bulletin-derived biotic-risk signaling co-vary with grape productivity in Romania. Integrating official county statistics on on-bearing vineyard area and yield (2014–2024), ERA5-based climate descriptors, and a warning-frequency index extracted from publicly available phytosanitary bulletins, the results indicate a consistent shift toward a more challenging production environment characterized by systematic warming, high precipitation variability with localized drying tendencies, and heightened yield instability across major vineyard counties.

Across the 10 focal counties, annual mean temperature increases are directionally consistent, and the late period culminates in exceptionally warm conditions, while precipitation exhibits pronounced interannual swings and predominantly negative short-window trends in several locations. Against this background, vineyard productivity shows large county-year dispersion and a coherent late-period weakening: in every county, yield in 2024 is lower than in 2021, indicating a broad productivity contraction expressed on a per-hectare basis. The bulletin-derived signal is dominated by the canonical vineyard threat complex—powdery mildew (*Erysiphe necator*), downy mildew (*Plasmopara viticola*), mites, and grape moth (*Lobesia botrana*)—and warning frequencies are concentrated in a subset of counties with intensive viticulture and strong advisory activity. Together, these patterns support the interpretation that recent climate conditions are compatible with both direct physiological stress on vines (heat and moisture limitation) and an increased management burden reflected in more frequent biotic-risk advisories, coinciding with the period of greatest yield deterioration.

The study's key contribution is methodological: it demonstrates how openly accessible national statistics, reanalysis climate data, and phytosanitary bulletins can be harmonized into an annually updateable monitoring system for climate-sensitive viticulture risk. At the same time, the warning-frequency index should be interpreted as a surveillance and risk-communication proxy, not field-measured incidence, and annual climate aggregates may mask the within-season timing that drives mildew and pest dynamics. Future work should therefore prioritize phenology-aligned growing-season indicators (e.g., wetness sequences, hot-day frequency/VPD) and higher-resolution spatial averaging over vineyard footprints to strengthen attribution. Even with these limitations, the integrated evidence highlights the need for regionally differentiated adaptation centered on risk-based monitoring, forecast-informed spray timing, and integrated pest management, particularly in counties where rapid warming co-occurs with drying tendencies and the strongest late-period yield declines.

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