

Artificial intelligence for predicting the mycelial dynamics of *Tuber aestivum*: a proof-of-concept

[Intelligenza artificiale per la previsione della dinamica miceliale di *Tuber aestivum*: un prototipo metodologico]

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Abstract

The hypogeous dynamics of *Tuber aestivum* remain a critical knowledge gap for truffle cultivation. This paper presents a proof-of-concept of a lightweight workflow based on artificial intelligence (AI), designed to generate site-specific and verifiable forecasts of seasonal mycelial activity using only routine agrometeorological data and a minimal number of direct observations. The pipeline integrates: (i) ecological rules encoding known constraints for ectomycorrhizal fungi; (ii) a penalized logistic model trained on derived meteorological variables; and (iii) bootstrap resampling to quantify predictive uncertainty. Applied to two experimental truffle grounds in northeastern Sicily, the model indicated activation windows at the end of summer in Motta Camastra—interrupted by brief droughts but recovering after autumn rains—and a narrower, more intermittent activity in Poggio di Alcanterra, subject to higher evaporative demand. Independent qPCR checks were qualitatively consistent with the conservative thresholds adopted by the model (absence at 35 cm; borderline detection at 20 cm). Emphasis is placed on methodology rather than generalization: the framework translates continuous climatic signals into falsifiable hypotheses on mycelial persistence, indicating when to sample (qPCR, GPR) and when to intervene in management (irrigation, soil care). By providing transparent rules, derived variables, and an uncertainty system, the approach is intended as a transferable tool for Mediterranean truffle grounds, to be further refined through denser qPCR transects and repeated time-series validations.

Keywords: *Tuber aestivum*; truffle cultivation; mycorrhizal dynamics; artificial intelligence; agrometeorological modeling

Abstract

La dinamica ipogea di *Tuber aestivum* rappresenta ancora una lacuna critica per la coltivazione del tartufo. Questo articolo presenta un prototipo metodologico (proof-of-concept) di un flusso di lavoro leggero basato su intelligenza artificiale (IA), progettato per generare previsioni specifiche per sito e verificabili sull'attività miceliale stagionale utilizzando esclusivamente dati

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agrometeorologici di routine e un numero minimo di riscontri diretti. La pipeline integra: (i) regole ecologiche che codificano vincoli noti per i funghi ectomicorrizici; (ii) un modello logistico penalizzato addestrato su variabili meteorologiche derivate; e (iii) bootstrap per quantificare l'incertezza predittiva. Applicato a due tartufaie sperimentali della Sicilia nord-orientale, il modello ha indicato finestre di attivazione a fine estate a Motta Camastra - interrotte da brevi siccità ma con recupero dopo le piogge autunnali - e un'attività più ristretta e intermittente a Poggio di Alcanterra, soggetto a maggiore domanda evaporativa. I controlli qPCR indipendenti sono risultati qualitativamente coerenti con le soglie conservative adottate dal modello (assenza a 35 cm; rilevazione borderline a 20 cm). L'accento è posto sulla metodologia più che sulla generalizzazione: il framework traduce segnali climatici continui in ipotesi falsificabili sulla persistenza miceliale, indicando quando campionare (qPCR, GPR) e quando intervenire nella gestione (irrigazione, cura del suolo). Fornendo regole trasparenti, variabili derivate e un sistema di incertezza, l'approccio si propone come strumento trasferibile ad altre tartufaie mediterranee, da affinare ulteriormente tramite transepti qPCR più densi e serie temporali ripetute.

Parole chiave: *Tuber aestivum*; coltivazione del tartufo; dinamiche micorriziche; intelligenza artificiale; modellizzazione agrometeorologica

Introduction

Quantifying truffle mycelium in soil remains a challenge. Although qPCR enables sensitive, species-specific detection, results are influenced by soil heterogeneity, extracellular DNA, and methodological variability (Gryndler et al. 2013; Bustin et al. 2009). Seasonal dynamics are known to respond to moisture pulses and temperature variations; instrumental studies have tracked primordia through soil CO₂ fluxes and GPR imaging (Pacioni et al. 2014). Artificial intelligence offers a complementary tool, capable of transforming continuous meteorological inputs into probabilistic activity windows that are useful for guiding targeted sampling and cultivation management.

Materials and Methods

Study sites and data

Two *Tuber aestivum* truffle grounds in northeastern Sicily were analyzed (Motta Camastra, Poggio di Alcanterra). Meteorological data (air temperature, humidity, precipitation, wind, derived vapor pressure deficit, and cumulative rainfall) were obtained from the SIAS network (Servizio Informativo Agrometeorologico Siciliano).

Independent qPCR controls at 20 cm and 35 cm from the trunk, performed at depths of 5–20 cm, were used exclusively as qualitative validation.

Modeling pipeline

1. Rule filter. Inclusion of ecophysiological envelopes (temperature, VPD, recovery from rainfall) to exclude implausible states.
2. Penalized logistic link. Meteorological variables (lagged cumulative rainfall, thermal means, VPD quantiles, series of dry days) were mapped to daily probabilities of activity (pt).

3. Uncertainty. Bootstrap (B=1000) provided percentile bands and a confidence rubric (high, moderate, low).
4. Operational thresholds. “Activation windows” when the lower quartile of $pt > 0.6$ for ≥ 5 consecutive days; “unstable windows” when the median of $pt > 0.6$ but with $IQR \geq 0.2$.

Results and Discussion

At Motta Camastra, the model indicated activation from late August to mid-September, interrupted by brief droughts but recovering in early October after moderate rainfall. The absence of qPCR at 35 cm and borderline detection at 20 cm matched the predictions.

At Poggio di Alcanterra, activation windows were shorter and more fragmented, consistent with higher evaporative demand and fewer effective rainfall pulses. This reflects previous evidence of humidity-driven oscillations and discontinuous persistence of *T. aestivum* (Pacioni et al. 2014; Gryndler et al. 2015).

Implications

Sampling. Align qPCR transects with predicted windows; compare depths to study vertical dynamics.

Management. Apply irrigation pulses after heat waves to stabilize activation; avoid soil disturbance during predicted peaks.

Validation. Integrate future GPR transects to link hypogeous signals with fruiting outcomes.

Conclusions

This AI framework demonstrates how routine meteorological data can be translated into transparent and falsifiable hypotheses on *T. aestivum* mycelial activity. While the present results are preliminary and based on limited field validation, the workflow shows potential transferability across sites and immediate usefulness in guiding sampling strategies and cultivation management in Mediterranean truffle grounds. The framework should be regarded as a methodological proof-of-concept rather than a definitive predictive tool. Expanding ground-truthing across multiple seasons and sites will be essential to refine the weight of climatic drivers and to assess the actual productive impacts.

Sintesi per il lettore italiano

Questo lavoro presenta un prototipo metodologico (proof-of-concept) che applica l'intelligenza artificiale allo studio della dinamica miceliale di *Tuber aestivum*. Utilizzando dati agrometeorologici di routine e un modello statistico leggero, il framework produce ipotesi verificabili sull'attività miceliale stagionale. I primi test condotti in due tartufige siciliane mostrano una coerenza qualitativa con controlli qPCR, confermando la potenzialità dell'approccio pur nella sua natura preliminare. Lo studio non fornisce risultati definitivi, ma apre la strada a future ricerche che integrino serie temporali più estese e validazioni sperimentali più robuste.

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Figure

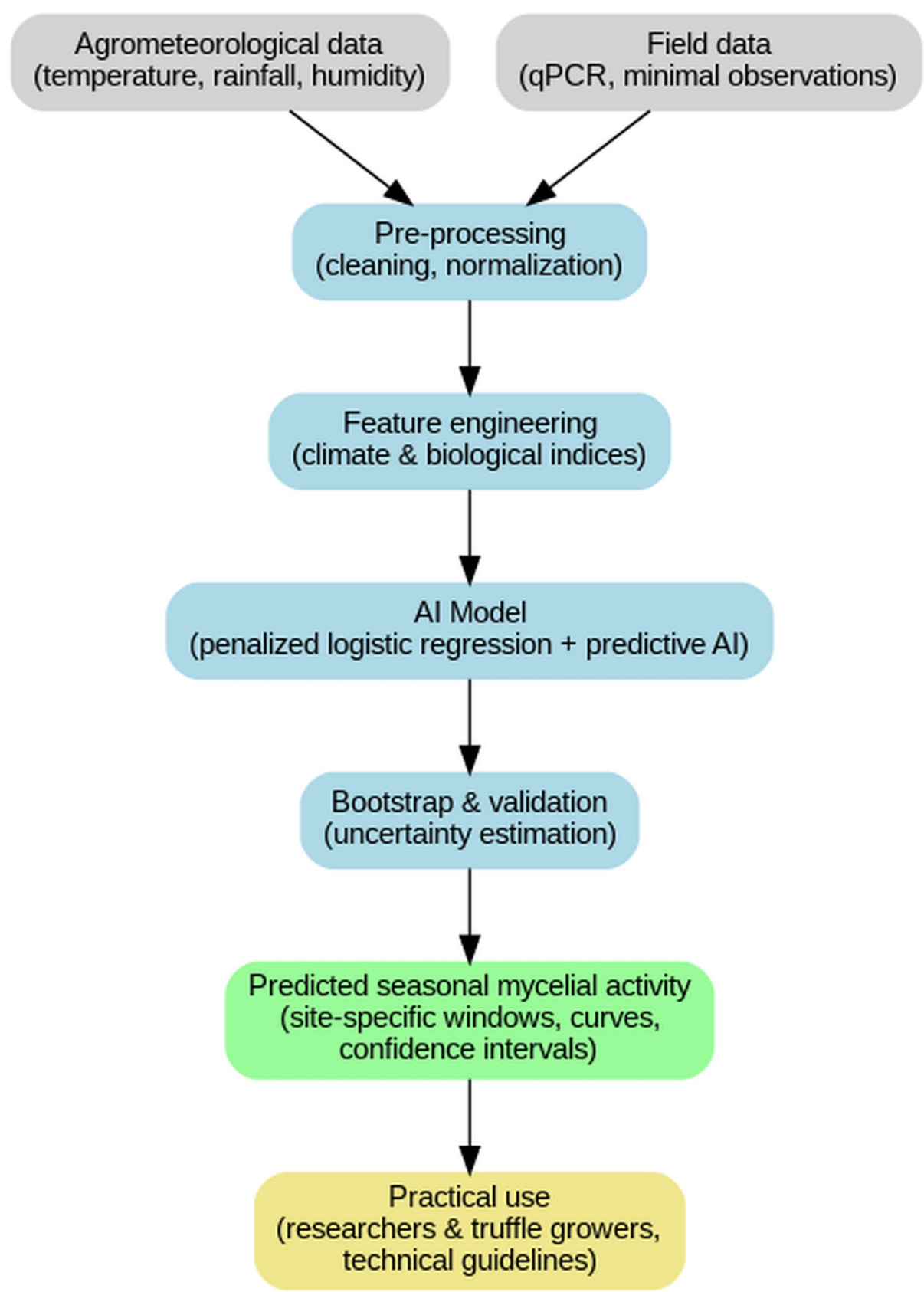


Figure 1. AI-based workflow for predicting *Tuber aestivum* seasonal mycelial activity from agrometeorological and field data.