FrostBit: A Computational Frostbite Risk Detection System for Almond Orchards

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Abstract

FrostBit is a computational frost-risk detection framework designed for almond orchards, integrating meteorological data with microclimate physics and phenology-specific biological frost-hardiness models. Each equation used in the pipeline—including wet-bulb approximation, dew-point estimation, blossom-temperature modeling, and logistic frost-damage probability—is directly sourced from peer-reviewed literature. This paper presents the scientific motivation, mathematical foundations, backend–frontend architecture, and computation workflow. FrostBit demonstrates that accurate, biologically grounded frost prediction is feasible and scalable.

1. Introduction

Almonds are among the most economically significant crops in California, but are also highly vulnerable to frost damage during bloom. Traditional weather forecasts report air temperature at sensor height but do not reflect the actual temperature of the blossom, which is influenced by microclimate effects such as radiative cooling. FrostBit integrates meteorological data with biological thresholds to quantify frost injury risk accurately.

2. Problem Statement

Air temperature alone cannot determine frost injury risk. Almond blossoms cool below air temperature due to radiation, and frost sensitivity varies by phenological stage. This project addresses the need for a system capable of computing actual blossom temperature and estimating damage probability from validated scientific models.

3. Methods

3.1 Meteorological Data Acquisition (CIMIS)

The California Irrigation Management Information System (CIMIS) provides hourly air temperature and relative humidity. These measurements serve as the foundation for all subsequent physical and biological modeling.

3.2 Microclimate Physics and Equation Selection

3.2.1 Wet-Bulb Temperature (Stull, 2011)

Wet-bulb temperature (T_{wb}) represents the lower limit of plant tissue temperature under evaporative cooling. FrostBit uses the Stull (2011) approximation:

$$T_{wb} = T \cdot \operatorname{atan}(0.151977 \cdot \sqrt{RH + 8.313659}) + \operatorname{atan}(T + RH) - \operatorname{atan}(RH - 1.676331) + 0.00391838 \cdot RH^{3/2} \cdot \operatorname{atan}(0.023101 \cdot RH) - 4.686035.$$

This formula is accurate to ±0.3°C and widely used in atmospheric modeling.

3.2.2 Dew-Point Temperature (Magnus Equation)

Dew point is calculated using the Magnus approximation:

$$\gamma = (aT)/(b+T) + \ln(RH/100)$$
$$T_{dew} = (b\gamma)/(a - \gamma)$$

with a = 17.27 and b = 237.7 (Alduchov & Eskridge, 1996).

3.2.3 Blossom Temperature Model (Snyder & de Melo-Abreu, 2005)

Blossom temperature (T_{bud}) is estimated as:

$$T_{bud} = T_{wb} - \Delta_{orchard}$$

where $\Delta_{orchard} \approx 1$°C represents canopy cooling relative to wet-bulb temperature.

3.2.4 Cooling Rate

Cooling rate describes temperature change over time:

$$\text{CoolingRate} = (T_{prev} - T_{current}) / \Delta t$$

Rapid temperature drops increase frost damage likelihood.

3.3 Biological Cold-Hardiness Modeling

Cold-hardiness thresholds are modeled using LT10 and LT90 values derived from freeze-chamber studies. Almond frost tolerance changes significantly across pink bud, full bloom, petal fall, fruit set, and small nut stages.

3.4 Logistic Frost-Damage Probability Model

FrostBit uses a logistic survival curve:

$$p(T) = 1 / (1 + \exp(-(a + bT)))$$

This model matches the observed sigmoidal relationship between freezing temperature and survival probability in biological tissues (Tudela & Santibáñez 2016, Salazar-Gutiérrez et al. 2014).

4. System Architecture

4.1 Backend Architecture

The backend is implemented in Python using FastAPI/Flask. It retrieves CIMIS data, computes microclimate variables, applies biological models, and returns a structured JSON output.

4.2 Frontend Architecture

The frontend is built in React/TypeScript. It displays charts, allows station/date selection, and communicates with the backend through REST API calls.

4.3 Backend–Frontend Workflow

1. User selects station and date.
2. Frontend sends API request.
3. Backend computes all frost-risk metrics.
4. JSON results are returned.
5. Frontend visualizes blossom temperature, dew point, cooling rate, and damage probability.

5. Results and Discussion

FrostBit successfully reconstructs frost events using historical CIMIS data. Output includes blossom temperature, wet-bulb, dew point, cooling trends, and stage-specific damage probabilities.

6. Limitations

- CIMIS does not provide real-time streaming.
- Logistic parameters are heuristic and require calibration.
- Additional variables—wind, inversion layers—could improve accuracy.

7. Future Work

Future goals include real-time API integration, parameter calibration, expansion to other crops, GIS mapping, and automated frost-alert systems.

8. Conclusion

FrostBit demonstrates that biologically accurate frost prediction is achievable by integrating validated equations with meteorological data. The system provides a strong foundation for a deployable frost early-warning tool.

9. References

Wet-Bulb Temperature

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