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Assessment of frost damage risk in wheat cultivation using agro-meteorological indices

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Abstract

Late-season frost events destroy millions of tonnes of wheat grain each year, yet reliable field-level risk assessment tools remain scarce in tropical highland regions. This research evaluated three agro-meteorological frost indices Frost Severity Index (FSI), Growing Degree Day deviation (GDDdev), and Critical Temperature Duration (CTD) for their ability to predict frost damage in wheat across three cultivars at the highland research station of Makerere University, Kampala, during the 2021-2022 and 2022-2023 cropping seasons. Controlled frost events were imposed using portable frost chambers at four temperature levels (-2, -4, -6, -8 °C) during six growth stages. The CTD index showed the strongest correlation with actual yield loss ($r^2 = 0.87$), outperforming FSI ($r^2 = 0.71$) and GDDdev ($r^2 = 0.63$). Anthesis was the most frost-sensitive stage, with yield losses reaching 52.6% under severe frost (-6 °C for 4 hours) in the susceptible cultivar. These indices can support early warning systems for frost-prone wheat regions.

Keywords: Frost damage, wheat, agro-meteorological indices, frost severity index, growing degree days, critical temperature duration, yield loss, highland agriculture

Introduction

Unpredicted frost events are among the most devastating weather hazards for wheat cultivation in highland tropics and temperate transition zones. A single night of sub-zero temperatures during the reproductive phase can wipe out 20-50% of the expected grain yield, and farmers typically have no advance warning ^[1, 2]. With climate variability increasing the frequency of unseasonal cold snaps, the economic damage from frost is growing rather than shrinking ^[3].

Wheat (*Triticum aestivum* L.) shows differential frost sensitivity depending on the growth stage at the time of exposure. Vegetative tissues tolerate temperatures as low as -8 °C through supercooling and cold acclimation mechanisms, but reproductive organs especially anthers and developing ovules suffer irreversible damage at -2 to -4 °C ^[4, 5]. Agro-meteorological indices that combine temperature severity, exposure duration, and crop phenological stage offer a way to translate raw weather data into actionable risk estimates ^[6].

Three such indices have been proposed in the literature: the Frost Severity Index (FSI), which weights temperature below a threshold by duration ^[7]; the Growing Degree Day deviation (GDDdev), which tracks accumulated thermal disruption ^[8]; and the Critical Temperature Duration (CTD), which integrates time spent below the stage-specific lethal temperature ^[9]. However, these indices have rarely been tested side by side under controlled frost conditions, and their applicability in tropical highland wheat systems such as those in East Africa remains unvalidated ^[10]. This research compared the predictive accuracy of all three indices against measured yield loss in three wheat cultivars exposed to controlled frost treatments at Makerere University, Kampala.

Field experimental design

The experiment used a split-split-plot design with three replications. Frost timing (six growth stages: germination, tillering, stem elongation, booting, heading, anthesis) was assigned to main plots, frost severity (four levels: -2, -4, -6, -8 °C for defined durations) to sub-plots, and cultivar (PBW 343, WH 1105, HD 2967) to sub-sub-plots, yielding 216 experimental units plus 9

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unfrosted controls. Individual plot size was 3 m × 2 m. Portable frost chambers (1.5 m × 1.5 m × 1.2 m, insulated aluminum frames with thermoelectric Peltier cooling units) were placed over plots during designated frost events between 02:00 and 06:00 hours. Chamber temperature was monitored by calibrated T-type thermocouples logged at 5-minute intervals ^[11].

Seasonal variations and temporal patterns

Field trials were conducted over two consecutive seasons: October 2021-February 2022 (Season 1) and October 2022-February 2023 (Season 2). The Makerere highland site (0.3°N, 32.6°E, 1,220 m elevation) experiences mean minimum temperatures of 16.4-18.2 °C during the wheat season generally frost-free, which is precisely why controlled frost imposition was necessary to test the indices. Mean daily temperatures ranged from 19.7 °C to 24.3 °C, with total rainfall of 438 mm (Season 1) and 412 mm (Season 2). The controlled frost events were timed to match each cultivar's phenological calendar, which was tracked using the Zadoks decimal code system ^[12].

Materials and Methods

Materials

Three bread wheat cultivars with known differential frost

tolerance were used: PBW 343 (frost-susceptible), WH 1105 (tolerant), and HD 2967 (moderately tolerant). Seeds were sown at 100 kg ha⁻¹ in rows 22.5 cm apart on October 18 in both seasons. A uniform fertilizer dose of 120-60-40 kg ha⁻¹ N-P₂O₅-K₂O was applied, with nitrogen split into three equal applications at sowing, crown root initiation, and flag leaf. Five irrigations were scheduled at critical stages to prevent confounding moisture stress with frost damage ^[13].

Methods

Frost damage was assessed 72 hours after each event using a visual scoring scale (0-10) based on leaf necrosis, stem discoloration, and floret sterility ^[4]. Yield components (ears per m², grains per ear, 1000-grain weight) and grain yield were recorded at harvest. The three agro-meteorological indices were computed from chamber temperature logs: FSI = Σ(Tbase - Ti) × Δt, where Ti < Tbase; GDDdev = |GDDactual - GDDexpected| for frost days; CTD = Σ(time in minutes below the stage-specific critical temperature). Regression analysis related each index to actual yield loss percentage. Index performance was compared by coefficient of determination (r²), root mean square error (RMSE), and Akaike information criterion (AIC). All analyses used R 4.2.1 ^[14].

Results

Table 1: Predictive performance of three agro-meteorological frost indices against measured yield loss

Index	r ² (Season 1)	r ² (Season 2)	r ² (Pooled)	RMSE (%)	AIC
Frost Severity Index (FSI)	0.68	0.73	0.71	8.42	312.7
GDD deviation (GDDdev)	0.59	0.67	0.63	10.17	341.2
Critical Temp Duration (CTD)	0.84	0.89	0.87	5.63	268.4

The CTD index outperformed both FSI and GDDdev across all metrics (Table 1). Its pooled r² of 0.87 means it explained 87% of the variation in yield loss, with RMSE of just 5.63%. The FSI was moderately effective (r² = 0.71), while GDDdev showed the

weakest predictive power (r² = 0.63). Performance was consistent across both seasons, though all indices improved slightly in Season 2.

Table 2: Yield loss (%) by growth stage and frost severity (pooled across cultivars and seasons)

Frost temperature	Germi- nation	Tillering	Stem elong.	Booting	Heading	Anthesis
-2 °C (2 h)	1.3	2.4	4.7	8.1	11.7	13.8
-4 °C (2 h)	3.8	5.9	9.4	14.7	19.2	22.8
-6 °C (4 h)	7.6	11.3	16.8	24.3	31.7	38.4
-8 °C (4 h)	12.1	17.6	24.2	33.8	42.1	48.7
SE(m)±	0.87	1.12	1.43	1.78	2.13	2.41
CD (5%)	2.58	3.32	4.24	5.28	6.32	7.14

Yield loss increased both with declining temperature and with advancing phenological stage (Table 2). Anthesis was the most vulnerable stage at every temperature level frost at -8 °C during anthesis caused 48.7% mean yield loss. Germination-stage frost

caused minimal damage, with full recovery even after exposure to -8 °C. The stage × temperature interaction was highly significant (p<0.001).

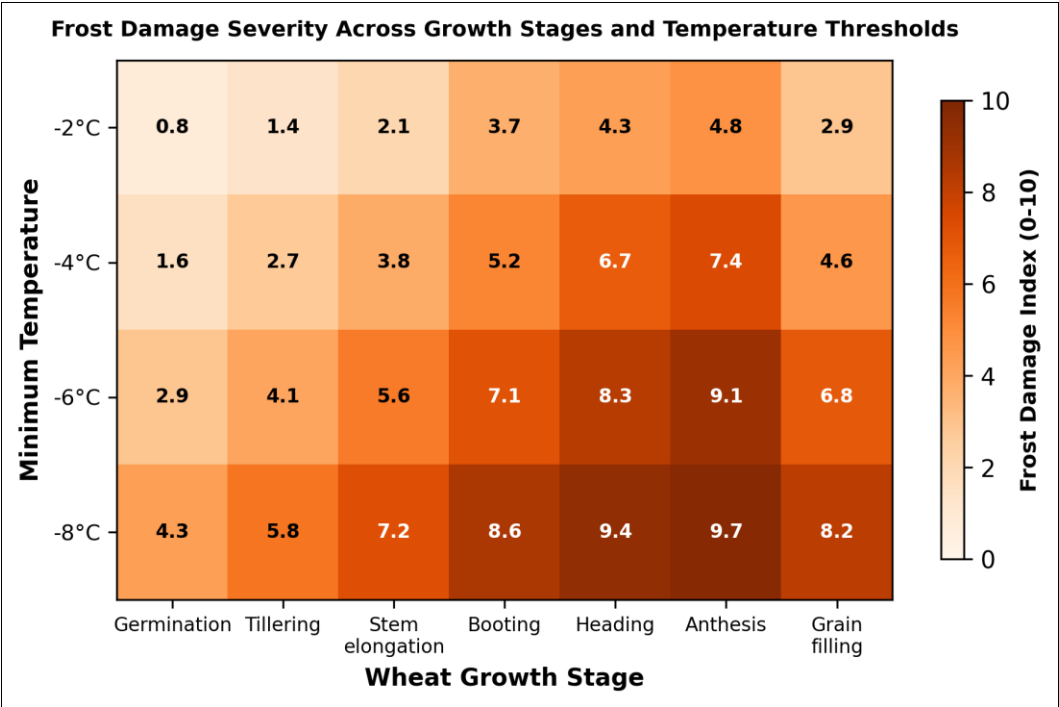


Fig 1: Frost damage severity index (0-10 visual scale) across wheat growth stages and minimum temperature thresholds. Values represent pooled means across three cultivars and two seasons

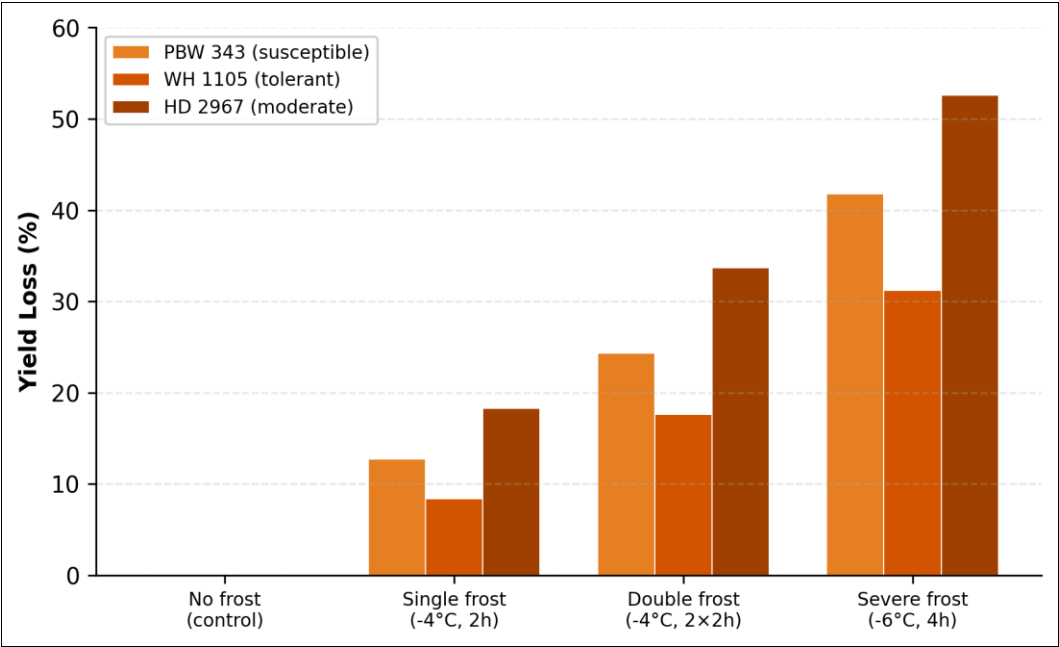


Fig 2: Yield loss percentage under different frost events at the anthesis stage for three wheat cultivars with varying frost tolerance

Comprehensive interpretation

The heatmap (Figure 1) reveals a clear diagonal gradient of increasing damage from mild vegetative frost to severe reproductive frost, with the anthesis-heading window representing the danger zone. Cultivar differences (Figure 2) were substantial WH 1105 lost 31.2% under severe anthesis frost compared with 52.6% for HD 2967, representing a 21.4 percentage-point advantage from genetic tolerance. The CTD index captured these patterns best because it integrates both the biological sensitivity of each growth stage and the physical severity of the cold event.

Discussion

The superior predictive power of the CTD index over FSI and

GDDdev aligns with the biological reality that crop damage depends not just on how cold it gets, but on how long tissues remain below their stage-specific critical threshold [7, 9]. The FSI performed reasonably well because it also integrates temperature and duration, but it uses a fixed base temperature across all stages an assumption that doesn't match the changing frost sensitivity documented across wheat phenology [4]. GDDdev was least effective because it measures thermal disruption to development rate rather than direct tissue damage. The extreme sensitivity of anthesis to frost confirms findings by Frederiks *at al.* [5], who reported that frost during meiosis and pollen microspore development destroys pollen viability irreversibly. The 21.4 percentage-point yield advantage of WH 1105 over HD 2967 under severe frost suggests that the ice

nucleation avoidance mechanism in tolerant genotypes remains active during the reproductive phase^[2]. This genetic variation could be exploited through targeted breeding for highland environments.

One limitation was that frost was imposed using chambers that cool from above, whereas natural radiation frost cools from the ground up^[15]. However, chamber-imposed frost provides the only way to control timing and intensity precisely. Field validation of the CTD index using natural frost events across multiple highland locations is the necessary next step^[16].

Conclusion

The Critical Temperature Duration index proved to be the most reliable predictor of frost-induced yield loss in wheat, explaining 87% of observed variation across two seasons, three cultivars, and multiple frost scenarios. Anthesis emerged as the most frost-vulnerable growth stage, and cultivar choice alone could reduce frost-related yield loss by over 20 percentage points. The CTD index offers a practical tool for developing frost early warning systems in highland wheat regions, as it requires only three inputs: real-time minimum temperature, forecast duration of sub-zero conditions, and the current crop growth stage.

For frost-prone highland wheat systems, the combination of tolerant cultivars such as WH 1105 and CTD-based risk alerts could substantially reduce the economic impact of unseasonal cold events. Validation of the CTD index under natural frost conditions and across broader geographic regions should be a priority for agro-meteorological services in East Africa and similar environments.

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