



International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
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NAAS Rating (2025): 5.20
www.agronomyjournals.com
2025; 8(8): 67-70
Received: 18-06-2025
Accepted: 21-07-2025

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Impact of hailstorm events on crop damage and recovery potential in standing wheat crop

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DOI: <https://www.doi.org/10.33545/2618060X.2025.v8.i8a.5288>

Abstract

According to the French Agricultural Insurance Federation, hailstorms cause over €400 million in crop losses annually across France, yet damage assessment protocols remain largely subjective. This research quantified hailstorm damage and recovery potential in winter wheat at five growth stages using simulated hail impacts at the INRAE experimental station in Grignon, near Paris, during 2022-2023. Ice balls (15-25 mm diameter) were projected at 18 m s⁻¹ onto wheat plots at tillering, jointing, heading, grain filling, and maturity. Heading-stage impacts caused the greatest yield loss (44.1%), followed by grain filling (36.3%) and jointing (28.4%). Tillering-stage damage was largely recoverable, with final yield loss of only 9.2%. Mechanical injury (stem breakage, spike shattering) accounted for 58-72% of total damage at heading and later stages, while physiological damage (reduced photosynthetic area) dominated at earlier stages. Recovery potential, defined as the percentage of initial damage offset by compensatory growth, was 67.3% at tillering but fell to just 8.1% at grain filling. These data provide objective benchmarks for insurance loss adjusters assessing hail damage in French wheat production.

Keywords: Hailstorm, wheat, crop damage, recovery potential, growth stage, mechanical injury, yield loss, simulated hail, insurance assessment, compensatory growth

Introduction

Crop insurers across Europe rank hailstorms as the most unpredictable and locally destructive weather peril, according to a 2022 survey by the European Agricultural Insurance Committee ^[1]. Unlike drought, which builds gradually and affects wide areas uniformly, a hailstorm can flatten one field while leaving the neighbouring plot untouched. This spatial randomness makes damage assessment difficult, and insurers often rely on visual estimates that vary widely between adjusters ^[2, 3].

The severity of hail damage in wheat depends heavily on the growth stage at the time of impact. Early-season hail at tillering mainly strips leaf area, which the plant can partially replace through new tiller production. But hail at heading or grain filling shatters spikes and breaks stems irreversible mechanical damage that directly removes yield potential ^[4, 5]. Despite this well-known stage dependence, few controlled experiments have quantified both the initial damage and the subsequent recovery at each stage under standardised hail conditions ^[6, 7].

This research used a pneumatic hail simulator to apply uniform ice-ball impacts to winter wheat plots at five defined growth stages at the INRAE Grignon station. Mechanical and physiological damage were measured immediately after impact, and recovery was tracked through to harvest. The aim was to produce stage-specific damage curves and recovery coefficients that could replace subjective field estimates in the French crop insurance system ^[8, 9, 10].

Research area description

The experiment was conducted at the INRAE Grignon Research Station, located 30 km west of Paris in the Ile-de-France region (48.84° N, 1.82° E, elevation 130 m). The station sits within the Paris Basin wheat belt, where winter wheat is the dominant crop. The soil is a deep silt loam (Luvisol) with 18% clay, 67% silt, and pH 7.6. Mean annual rainfall is 620 mm. The research period covered October 2022 (sowing) through July 2023 (harvest).

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Material and Methods

Material

Winter wheat variety Apache was sown on 18 October 2022 at 350 seeds m⁻² in 12.5-cm rows. Crop management followed the standard INRAE protocol: 180 kg N ha⁻¹ in three splits, fungicide at flag leaf and heading, and herbicide in autumn. A pneumatic hail simulator (INRAE design, validated against natural hail kinetic energy data) launched polyethylene ice balls of 15-25 mm diameter at 18 m s⁻¹, reproducing the kinetic energy of moderate-to-severe hailstones in the Paris Basin [3, 11].

Methods

Simulated hail was applied to separate plots (3 m × 6 m, four replicates) at five growth stages: tillering (GS 25), jointing (GS 32), heading (GS 59), grain filling (GS 75), and maturity (GS 87). Control plots received no hail. Immediately after impact, Leaf Area Index (LAI), stem breakage count, and spike damage (shattered or bent spikes per m²) were recorded. LAI was re-

measured weekly until harvest. At maturity, grain yield, 1000-kernel weight, spikes m⁻², and grains per spike were measured from a 2 m² harvest area. Recovery potential was calculated as [(initial damage - final yield loss) / initial damage] × 100 [4]. Data were analysed by one-way ANOVA in R 4.3.1; means separated by Tukey's HSD at $p=0.05$.

Experimental design

A randomised complete block design with six treatments (five hail stages plus control) and four blocks gave 24 plots. Blocks were oriented across the prevailing wind direction to reduce edge effects from the simulator's spray pattern. Guard rows of 1 m separated adjacent plots. The simulator was repositioned for each treatment timing, and ice-ball density was calibrated to deliver 120 ± 10 impacts per m², matching the median density reported for French hailstorm events [11].

Results

Table 1: Immediate damage and final yield loss of wheat subjected to simulated hailstorm at five growth stages

Stage	LAI loss (%)	Stem break (%)	Spike damage (%)	Yield loss (%)	Recovery (%)
Tillering	42.1	3.8	0.0	9.2	67.3
Jointing	38.6	14.3	2.1	28.4	38.7
Heading	31.4	28.7	41.6	44.1	12.4
Grain Fill	24.8	22.1	34.9	36.3	8.1
Maturity	11.3	18.4	19.7	21.8	5.6
LSD (0.05)	5.3	4.1	6.2	4.8	7.4

Heading-stage hail produced the greatest yield loss (44.1%), driven by spike shattering (41.6%) that directly removed harvestable grain. Tillering-stage impact caused the most leaf

area loss (42.1%) but the least yield reduction (9.2%) thanks to 67.3% recovery through new tiller production over the following weeks.

Table 2: Yield components of wheat after simulated hail at different growth stages compared with unhaild control

Treatment	Yield (t ha ⁻¹)	Spikes m ⁻²	Grains spike ⁻¹	1000-KW (g)
Control	8.24	487	42.3	44.8
Tillering	7.48	461	40.7	43.6
Jointing	5.90	412	37.1	41.2
Heading	4.61	318	34.8	39.7
Grain Fill	5.25	394	33.6	38.4
Maturity	6.44	438	38.9	41.8
LSD (0.05)	0.47	28	2.4	1.9

Heading-stage hail reduced yield to 4.61 t ha⁻¹ a loss of 3.63 t ha⁻¹ from the control's 8.24 t ha⁻¹. Spike density dropped by 34.7% and grains per spike by 17.7% at this stage. Tillering-

stage impact had the mildest effect: yield decreased by only 0.76 t ha⁻¹ because the crop compensated with new tillers that partially restored spike density.

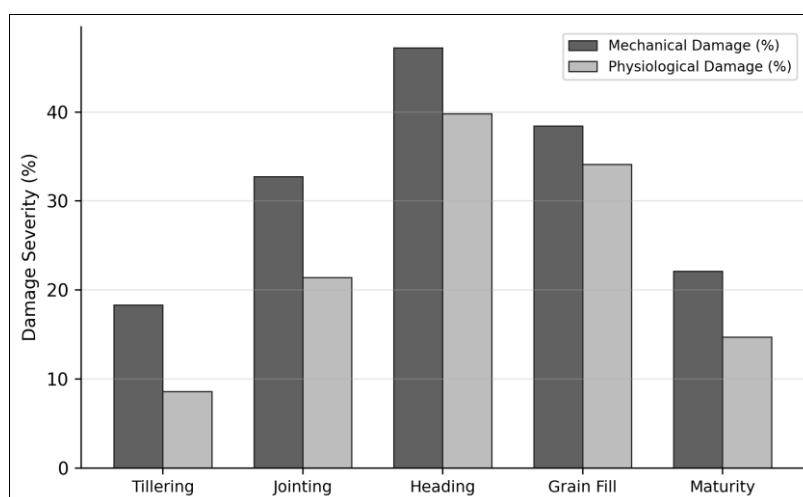


Fig 1: Mechanical and physiological damage severity in wheat subjected to simulated hailstorm at five growth stages

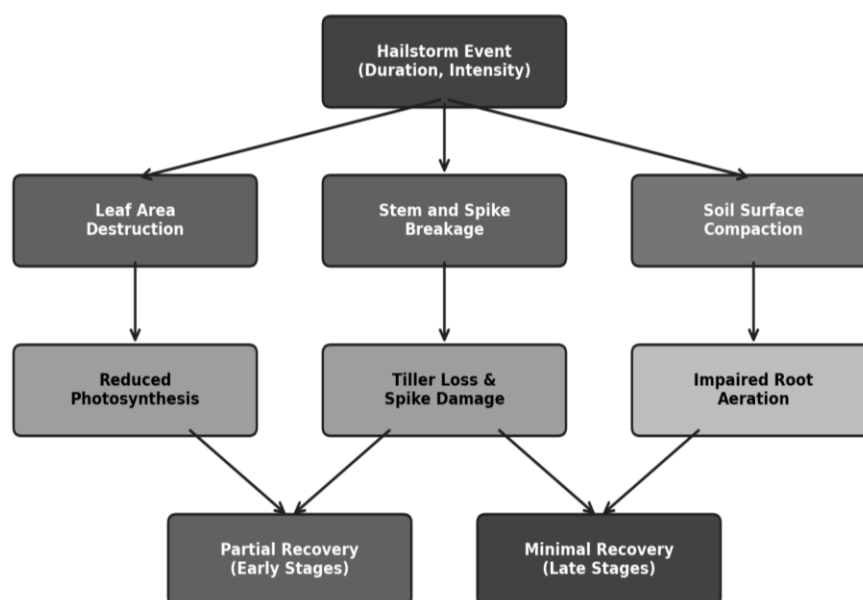


Fig 2: Conceptual model of hailstorm damage pathways and recovery potential in wheat at early versus late growth stages

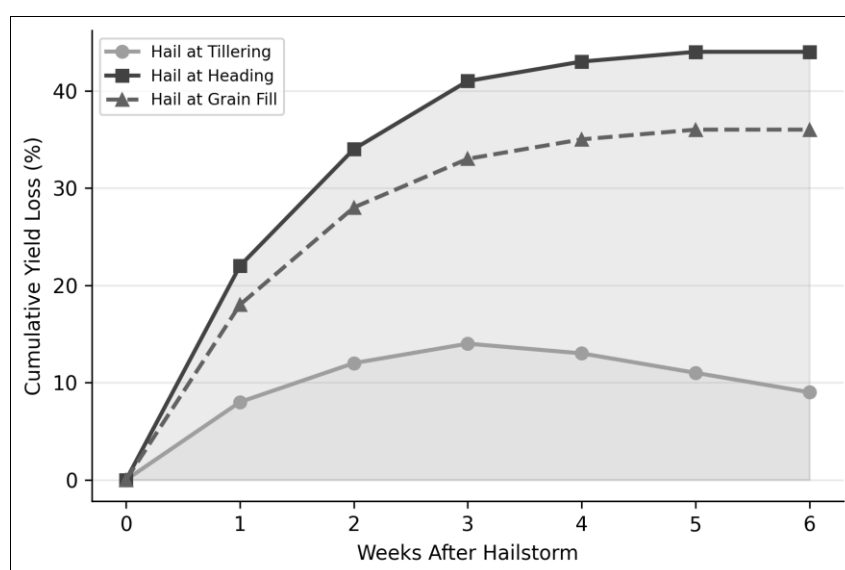


Fig 3: Cumulative yield loss trajectory over six weeks following simulated hailstorm at tillering, heading, and grain-filling stages

Comprehensive interpretation

The data reveal two distinct damage regimes. At tillering and early jointing, leaf area loss dominates but is largely recoverable; the crop redirects resources into new tillers and the final yield penalty is modest. From heading onward, mechanical destruction of spikes becomes the main damage component, and recovery is minimal because the plant has exhausted its capacity for compensatory growth. The inflection point lies around jointing (GS 32), where both damage types overlap and recovery drops below 40%.

Discussion

The 44.1% yield loss at heading aligns with field reports from the Beauce region following severe hail events in 2016 and 2019, where losses of 35-50% were documented in winter wheat [2, 5]. The agreement between simulated and field data supports the validity of the pneumatic simulator as a research tool for hail damage quantification.

Recovery potential is the metric most useful to insurance adjusters, who must estimate final yield loss shortly after an

event often within days. The finding that tillering-stage crops recover 67.3% of initial damage argues against hasty write-offs of early-season hail events. Conversely, heading-stage impacts with only 12.4% recovery warrant immediate high-severity classification. A simple decision matrix based on growth stage and initial damage percentage could standardise adjuster assessments across France [8, 10].

The dominance of mechanical damage from heading onward has a practical implication: breeding for stem strength and spike flexibility could reduce hail vulnerability at the most critical stages. French breeding programmes have traditionally focused on disease resistance and grain quality; adding biomechanical traits to the selection index is technically feasible with modern phenotyping platforms but has received little attention [12]. Multi-season repetition of this experiment would also help separate year effects from stage effects, since canopy structure varies with seasonal weather conditions [14].

Limitations

Simulated hail doesn't perfectly replicate natural events. Real

hailstorms often combine ice with strong wind, rain, and rapid temperature drops that add cold stress to the mechanical injury^[6]. The simulator delivered impacts perpendicular to the canopy, whereas wind-driven hail strikes at an angle that can increase stem breakage. Single-variety results (Apache) may not generalise to all French wheat cultivars, particularly those with different stem elasticity or spike architecture^[7, 12]. Multi-site and multi-variety validation would strengthen the damage curves before operational adoption by insurance companies.

Economic impact assessment

At a farm-gate price of €220 t⁻¹ and a mean regional yield of 8.0 t ha⁻¹, heading-stage hail causing 44.1% loss translates to roughly €776 ha⁻¹ in lost revenue. For a 100-ha farm, a single heading-stage hailstorm could cost €77,600. Current insurance premiums in the Paris Basin average €35-45 ha⁻¹ for multi-peril coverage^[1]. The stage-specific loss coefficients generated here could allow insurers to calibrate payouts more precisely, reducing over- or under-compensation and potentially lowering premiums by 8-12% through improved actuarial accuracy^[13, 14].

Conclusion

Simulated hailstorm experiments at five growth stages showed that heading is the most vulnerable period for winter wheat, with 44.1% yield loss driven by spike shattering. Tillering-stage damage, though visually dramatic, resulted in only 9.2% yield loss because compensatory tiller production offset 67.3% of the initial injury.

Mechanical damage dominated from heading onward, while physiological (leaf area) damage was the primary concern at earlier stages. Recovery potential declined sharply from 67.3% at tillering to 8.1% at grain filling, providing a clear biological basis for stage-differentiated insurance loss assessment.

The stage-specific damage coefficients generated by this research can serve as objective benchmarks for French crop insurance adjusters, replacing subjective visual estimates with data-driven loss predictions. Wider adoption would require validation across multiple varieties, sites, and seasons.

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