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An Intermediate Wheatgrass model for APSIM Next Generation

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ABSTRACT

Perennial cereals, for dual purpose grain and forage production, are being considered as an alternative to annual cereals in many grazing and cropping enterprises. Field experiments in NSW Australia and elsewhere have identified candidate species, such as intermediate wheatgrass and mountain rye, which produce both grain and biomass over a two-to-three year period. Existing experimental data pertaining to the phenology and yields of perennial cereals are mostly from higher latitude temperate regions of North America. There are sparse data to inform the likely growth and yields of perennial cereals in warmer latitudes. This study aimed to address this gap using the APSIM Next Generation crop simulation program. A model for one of the candidate perennial cereals, intermediate wheatgrass, was constructed within APSIM. The model was then used to predict the likely phenology, biomass, and grain yields of intermediate wheatgrass in diverse environments under varying management regimes. The model was parameterised using phenology and yield datasets from Australia and North America. Validation of the model, using a different selection of datasets, indicated a strong phenology prediction accuracy (r^2=0.96, RMSE=7.94 (Zadoks scale)). Prediction accuracies for above ground biomass and grain yield were acceptable (r^2=0.75, RMSE=2372 kg/ha and r^2=0.80, RMSE=148 kg/ha respectively). The model responded appropriately to irrigation and fertiliser inputs. Further simulations, using a transect of locations from sub-tropical Queensland to temperate Tasmania, indicated that successful grain production, given the current vernalisation requirements of intermediate wheatgrass, is likely restricted to temperate zones of the current cereal cropping regions in Australia. The Intermediate Wheatgrass model is the only comprehensive perennial grains model available at present. It will be a valuable tool for both plant breeders and farm planners when developing new cultivars and/or defining suitable geographical regions for new perennial grains crops, such as intermediate wheatgrass.

1. Introduction

Introducing perennial cereals into agricultural production systems has many potential advantages including reduced tillage, improved soil organic carbon content (Kim et al., 2022b; Tang et al., 2023), reduced nutrient leaching (Culman et al., 2013), and potential production benefits from reduced farm inputs and extra grazing for livestock (Bell, 2010; Newell and Hayes, 2017). However, new farming methods (such as utilising perennial grain species) present risks for farmers, including the unknown viability of new crop types across different locations, soil types, and seasonal conditions. There needs to be a knowledge base built to increase the degree of certainty for new farming systems. Modelling is a tool that can assist in the design of new farming systems, by considering a range of seasonal and management inputs, and forecasting the likely outcomes (Whitbread et al., 2010). Field data is expensive and time consuming to collect, with outcomes driven by the prevailing environmental conditions of soil and climate at the given site, while models can be long term and reflect climate rather than weather influences. Models also offer an efficient and faster approach for estimating crop response, to better target future field testing and research.

Perennial cereals are a relatively new concept in Australia. Limited efforts have been invested in the development of a perennial cereals crop

Abbreviations: APSIM, NSW, New South Wales, Agricultural Production Systems SIMulatorPMF Plant Modelling Framework; QLD, Queensland; AUS, Australia; RMSE, Root Mean Square Error; RSR, Root mean square error Standard deviations Ratio; SLA, Specific Leaf Area.

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model to examine their potential role in agriculture. The Agricultural Production Systems Simulator (APSIM), described by Holzworth et al. (2014), and the latest version, APSIM Next Generation (Holzworth et al., 2018), can simulate the growth of annual crops such as wheat, and also mixed and rotational cropping. There is presently no functionality for perennial grain crops in APSIM or APSIM Next Generation. APSIM Next Generation can, however, simulate the growth of other perennial plants, such as oil palm, pine trees, and perennial forages (e.g., chicory, red clover). It is proposed that these models can guide the creation of a perennial cereals model in APSIM Next Generation. The initial modification planned was to simulate the growth of the perennial grain and forage crop intermediate wheatgrass (IWG; *Thinopyrum intermedium*), as there is a wealth of experimental data available to parameterise a model for this species. This will provide foundational capacity for the modelling of other perennial cereals. With a perennial cereals model, APSIM Next Generation would have the ability to forecast likely outcomes when a perennial cereal is grown in monoculture, or possibly with a legume intercrop. The model could then provide insights into the best management choices for integrating perennial cereals into mixed livestock/grain farming systems. A perennial cereal model would be an important tool for researchers to understand which environmental and management factors are important, for plant breeders to gain insight into important traits, and for planners wishing to forecast likely forage production and crop yields when perennial cereals are grown in a range of geographical areas and environments.

Past modelling efforts have investigated possible methods of integrating perennial grains into farming systems. The economics of growing perennial wheat for dual purpose grazing and grain cropping were modelled by Bell et al. (2008) using the MIDAS (Model of the Integrated Dryland Agricultural System) platform, determining that the trade-off for lower perennial wheat grain yield could be compensated by increased forage production for grazing. Duchene et al. (2021) developed a phenological model for intermediate wheatgrass, based on the soil-crop model Simulateur mulTidiscplinaire pour les Cultures Standard (STICS) (Brisson et al., 2003). Jungers et al. (2018) also modelled the growth of intermediate wheatgrass by matching observed phenological stages (stem elongation, boot stage, anthesis, and maturity) to growing degree days using data from field experiments conducted in St. Paul and Rosemount in Minnesota USA. These models included equations to predict the stem elongation stage as a management guide for grazing, while maintaining the grain yield potential of the crop.

The APSIM Next Generation platform enables more comprehensive crop modelling than those previous initiatives. For example, it can predict the growth and yields of individual crop varieties of species such as wheat and can also simulate the growth of multiple species in the same paddock, such as pasture mixes grazed by livestock. This range of functionalities provided by APSIM Next Generation does not appear to be available in other contemporary crop modelling programs (e.g. DSSAT (Jones et al., 2003) and STICS (Brisson et al., 2003)). When developed, the APSIM Next Generation model would be an advance on current models, which focus on phenology prediction, with little or no biomass and grain yield predictive ability. Current models also lack the functionality to predict responses to a range of management actions. The proposed model will include all these functionalities.

The aim of this study was to construct an Intermediate Wheatgrass model within the APSIM Next Generation farming systems framework (Holzworth et al., 2018) that could replicate the phenology and yields of intermediate wheatgrass at diverse locations under a range of management systems. This would represent the first ever perennial cereals model within the APSIM framework and provide a significant advancement in the research capacity underpinning the development and deployment of perennial grains.

2. Materials and methods

2.1. Constructing the model within APSIM Next Generation

The Plant Modelling Framework (PMF) in APSIM Next Generation is designed to allow scientists to graphically construct models from small building blocks (Brown et al., 2014). The interface is designed such that no coding is generally needed and provides a library of prebuilt models and functions. For example, an interpolation of XY pairs can be added to a new model space or modified in an existing model. Models can be easily modified without recompilation. For management functions, scripts can be written that trigger actions at desired points in the simulation, e.g., a defoliation may be programmed to occur at a number of days after sowing, or when the crop has reached a stage of development. These scripts can be written in the C# language, and are compiled at program run time.

The Intermediate Wheatgrass model uses a subset of the available APSIM classes and functions that are provided for model development (class names are shown in italic font). The *Phenology* class tracks the development of the crop using *Phase* sub-classes, which each have targets such as thermal time, chilling hours, or photoperiod. Plant components are represented by an *Organ* class and a *Root* class. Sub-classes of *Organ* used are *SimpleLeaf*, *ReproductiveOrgan*, and *GenericOrgan*. The *Organ* classes use a *Biomass* sub-class to keep a daily track of live and dead biomass, and the biomass demands of each organ. The transfer of biomass between organs is arbitrated daily by the *Arbitrator* class.

2.2. Model datasets - parameterisation and validation

One of the aims of developing the Intermediate Wheatgrass model was to help plan where and under what management conditions a crop may be productively grown, both for forage and grain. The parameterisation datasets (Table 1) included a range of initial parameter values (such as thermal time between growth stages) from a spectrum of environmental conditions and locations where intermediate wheatgrass has been grown. The combination of experimental results from those studies, and from detailed glasshouse experiments e.g. (Innes et al., 2025b; Locatelli et al., 2022), were used for the initial model parameterisation. Where intermediate wheatgrass experimental parameter values were not available, values were inferred from other related models, such as the APSIM Wheat model (Brown et al., 2018). The parameter values were iteratively adjusted as necessary during the calibration process, to better match the phenology and yield outcomes observed in the parameterisation datasets. The phenology component was calibrated first, and then the components associated with biomass and grain yields. After parameterisation and calibration, validation simulations were run, comparing the model predictions with the observations from the validation datasets (Table 2). The parameterisation and validation datasets were sourced primarily from North America, as there were few available datasets from lower latitudes. The exception were datasets from field experiments at Cowra, NSW Australia and Pittsworth, QLD Australia (Innes et al., 2025a). Two of these datasets were used for parameterisation and one for validation. For both the parametrisation and validation phases, the soil types, meteorological conditions, and management actions were matched as closely as possible to the descriptions in the source publications in Tables 1 and 2.

2.3. Phenology

Other existing models within APSIM Next Generation including Wheat (Brown et al., 2018), Red Clover (Cichota, 2021), and Chicory (Cichota et al., 2020)) had examples of phenology sequences that included vernalisation and secondary induction phases, and a rewind phase (or *GotoPhase)* in the case of the perennial species (Red Clover and Chicory) models. The functionality of these phases were all requirements for the Intermediate Wheatgrass model implementation. The

Table 1
Parameterisation datasets used to develop the Intermediate Wheatgrass (IWG) APSIM Next Generation model.

Observed data	Location	Sowing	Fertiliser	Irrigation	Harvest	Sample size m^2	IWG cultivar	Reference
Phenology	Cowra, NSW AUS (−33.8, 148.7)	18/5/2022, 15 cm rows, 90 seeds/m^2	18/5/2022 NPK:25–5–8.8, 75 kg/ha	May 2022	4/2/2023, 8/2/2024 Harvest to 10 cm	0.15	CPI−148055 Land Institute KS USA 2008	Innes et al. (2025a)
Phenology	Pittsworth, QLD AUS (−27.76,151.57)	20/6/2022, 15 cm rows, 90 seeds/m^2	20/6/2022, NPK:15–4.4–11.5 + Urea 100 kg/ha each	June 2022	25/4/2023, 5/3/2024 Harvest to 10 cm	0.15	CPI−148055 Land Institute KS USA 2008	Innes et al. (2025a)
Phenology	St. Paul MN USA (44.99, −93.17)	5/9/2014, 15 cm rows, 12 kg/ha	5/4/2015, 6/4/2016, NH3NO4 40kgN/ha	None	4/8/2015, 29/7/2016, Harvest to soil level	0.025	4th generation Land Institute KS USA	Jungers et al. (2018)
Biomass, Grain	Hickory Corners, MN USA (42.4, −85.4)	12/11/2009, 15 cm rows, 310 seeds/m^2	MidN 23/04/2010, 26/05/2010 Urea 60 kg/ha. HighN 23/04/2010, 26/05/2010 Urea 110 kg/ha	None	26/09/2010, Harvest to 10 cm	0.25	(Cox et al., 2010) I5C1 Land Institute KS USA	Culman et al. (2013)
Phenology, Biomass, Grain	Roseau, MN USA (48.88, −95.85), Swift, MN. (48.87, 9–5.16)	28/8/2014, 15 cm rows, 145 seeds/m^2	14/4/2015, NH3NO4, 40 or 80 kgN/ha, 10/5/2016, 17/5/2017, Urea 40 or 80 kgN/ha	None	31/8/2015, 31/8/2016, 31/8/2017, Harvest to 7.5 cm	0.405	4th generation Land Institute KS USA	Fernandez et al. (2020)

The observed data values were used both as guidance in setting the initial parameter values (e.g., phenology timing) and for calibration result comparisons (e.g., biomass and grain yield predicted vs. observed). The harvest column contains the date and height above ground of each harvest. Some experiments span multiple years, as indicated by the harvest dates.

Table 2
Validation datasets for the Intermediate Wheatgrass (IWG) APSIM Next Generation model.

Observed data	Location	Sowing	Fertiliser	Irrigation	Harvest	Sample size m^2	IWG cultivar	Reference
Biomass	Cowra NSW AUS (−33.8, 148.7)	13/05/2013, 25 cm rows, 80 seeds/m^2	13/05/2013, DAP*.+ super phos.14:22:9 kgNPS/ha 13/05/2014, super phos. 15:19 kgPS/ha	Dec 2013	30/10/2013, 18/02/2014, Harvest to soil level	0.25	CPI−148055 Land Institute KS USA 2008	Hayes et al. (2017)
Biomass, Grain	St. Paul MN USA (44.99, −93.17)	05/09/2014, 15,30,61 cm rows, 12 kg seed/ha	05/04/2015, NH4NO3 40kgN/ha, 05/04/2015–17 Urea 50kgN/ha	None	04/08/2015, 04/08/2016, 04/08/2017, Harvest to 7.5 cm	0.42	4th Cycle Land Institute KS USA	Hunter et al. (2020a) and Hunter et al. (2020b)
Phenology	Rosemount MI USA (44.72, −93.1)	4/9/2015, 41&61 cm rows, 12 kg seed/ha	5/4/2015, 6/4/2016, NH3NO4 40kgN/ha,	None	Measuring phenology only	0.15	4th generation Land Institute KS USA	Jungers et al. (2018)
Phenology	Salina KS USA (38.77, −97.57)	26/9/2017, rows 30 cm, 5 mm deep	1/4/2019, Urea 174 kg/ha	None	Measuring phenology only	0.045	3rd−5th generation Land Institute KS USA	Barriball et al. (2022)
Biomass, Grain	Wooster, Ohio USA (40.76, −89.9)	27/08/2014, rows?, 16.8 kg seed/ha (140/sqm)	24/05/2014, MAP* 67 kg/ha, MOP* 67 kg/ha, Urea 45kgN/ha 19/8/2015, 30/03/2016, 15/08/2016, 04/04/2017, Urea 36kgN/ha	None	12/8/2015, 2/8/2016, 9/8/2017, Harvest to 50 cm	8.64	Land Institute KS USA	Pugliese et al. (2019)
Phenology, Biomass, Grain	St. Paul MN USA (44.99, −93.17)	1/9/2015, 1/10/2015, 15/12/2015, 1/9/2016, 15/10/2016	1/5/2015, 1/5/2016, Urea 67KgN/ha	None	14/8/2016, Harvest to 12 cm	1.2	4th generation Land Institute KS USA	Jungers et al. (2022)

*MAP mono-ammonium phosphate, DAP di-ammonium phosphate, MOP muriate of potash
The observed data values were used to validate the model after the parameterisation and calibration phases. The harvest column contains the date and height above ground of each harvest. Some experiments span multiple years, as indicated by the harvest dates.

phenology includes nine phases from *Germinating* to *Harvest*, with each phase starting and ending at one of nine stages (Table 3). In the APSIM Intermediate Wheatgrass model the transition between the *Germination* and *Emerging*, *Emerging* and *Vernalisation*, *Reproductive* and *Grainfilling*, and *Grainfilling* to *HarvestRipe* phases (Table 3) are all governed primarily by thermal time. Like many other cool climate grasses, intermediate wheatgrass requires dual-induction by vernalisation and photoperiod (increasing daylength) before proceeding to reproduction (Heide, 1994). This entails a period of cool temperatures (<5°C) and short days (<11 h), i.e. vernalisation, followed by long days (>13 h), i.e. secondary induction (Duchene et al., 2021; Heide, 1994; Ivancic et al., 2021; Locatelli et al., 2022). The transition from *Vernalising* to *Inducing* is controlled by a vernalisation days factor (accounting for low temperature duration). The transition from *Inducing* to *Reproductive* is controlled primarily by daylength (photoperiod). The transition from *Reproductive* to *GrainFilling* is slowed by both high temperature (Fig. 1) (Cicchino

Table 3
Phenology phases and stages used in the APSIM Next Generation Intermediate Wheatgrass model.

Phase Number	Phase Name	Initial Stage	Final Stage
1	Germinating	Sowing	Germination
2	Emerging	Germination	Emergence
3	Vernalising	Emergence	Induction
4	Inducing	Induction	StemElongation
5	Reproductive	StemElongation	Flowering
7	GrainFilling	Flowering	Ripening
8	Maturing	Ripening	Mature
9	Harvest	Mature	Rewind
10	GotoPhase	Rewind	Vernalising

The model uses targets (e.g., thermal time, vernalisation, photoperiod) to transition between phases. The stages define the start and end of each phase and are used by the model to determine the current growth stage of the crop.

et al., 2010), and leaf moisture stress (*[Leaf].FW*) (Chauhan et al., 2019).

Whether harvesting occurs in the *Harvest* phase can be controlled by management scripts. The default action is the *Harvest* phase proceeds to the *GoTo* phase which rewinds the phenology to the *Vernalising* phase. In the model *ThermalStressThreshold* (heat stress) and *FWStressThreshold* (water stress) constant values were defined. These constants can be interpreted by management scripts. This supplies reference values for the option of rewinding the phenology to the vegetative stage if a combination of conditions indicates a probable crop failure.

2.4. Cardinal temperatures and stress

The optimal and maximum growth temperatures were initially set to those suggested by Duchene et al. (2021), 35°C and 45°C respectively. These temperatures were adjusted during parameterisation and calibration (while also taking account of the experimental results from Pittsworth, QLD (Innes et al., 2025a) to values of 30°C and 35°C (Fig. 1).

2.5. Thermal time targets

Thermal time is calculated using the relationship described in Fig. 1. The average of eight three-hourly estimates of mean temperature (with a base of 0°C) gives a daily value in degree days. The thermal time targets between growth phases were initially parameterised with the aid of available experimental data, e.g., Lawrence (1957) for seedling emergence time targets, and Cattani and Asselin (2022), Barriball (2020), and Jungers et al. (2018) for other growth and reproductive stages. Vernalisation, growth and reproductive stage data were also available from field experiments conducted in Australia at contrasting locations near Cowra, NSW and Pittsworth, QLD (Innes et al., 2025a), and glasshouse experiments at Cowra (Innes et al., 2025b).

2.6. Vernalisation and induction

The vernalisation and inductive phase routines were partly adapted from the APSIM Next Generation Chicory model (Cichota et al., 2020), using the *Vernalisation* module from APSIM Next Generation. Vernalisation days are calculated using the relationship in Fig. 2, using the average of eight three-hourly estimates of mean temperature below 7°C (upper chilling temperature limit estimated by Duchene et al. (2021). After the target number of vernalising days (8 days) are achieved, the model waits for secondary induction requirements to be fulfilled, which is a progression to a target number of days, derived by a linear interpolation of the photoperiod length of the current day (relationship not shown). During the vernalisation and induction periods, photosynthetic activity and vegetative biomass accumulation continues. Data for vernalisation exposure periods and secondary induction daylengths were obtained from glasshouse experiments at Cowra (Innes et al., 2025b) and from data published by Duchene et al. (2021), Ivancic et al. (2021), and Locatelli et al. (2022).

2.7. Leaf

2.7.1. Photosynthesis

Biomass accumulation was modelled as a product of radiation use efficiency (RUE) and intercepted solar radiation. Photosynthesis parameters, including RUE, were initially set to match the parameters from the APSIM Next Generation Wheat model (Brown et al., 2018). It was assumed the photosynthesis rate for intermediate wheatgrass was similar to wheat, although there may be seasonal differences (Jaikumar

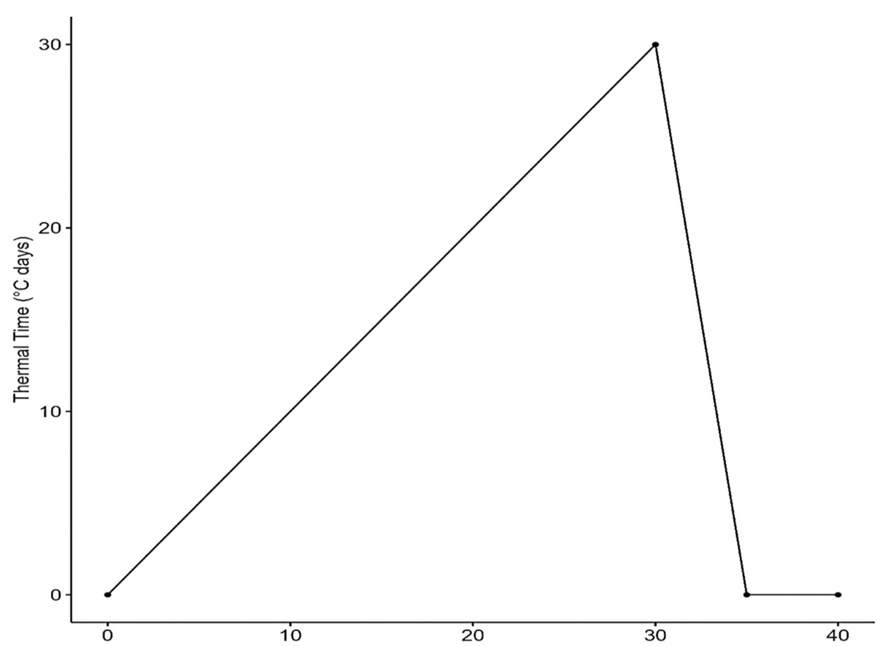

Fig. 1. Thermal Time progression (y-axis degree days) in relation to air temperature (x-axis). Greatest progression is at the optimal temperature, reducing to no progression at the maximum temperature.

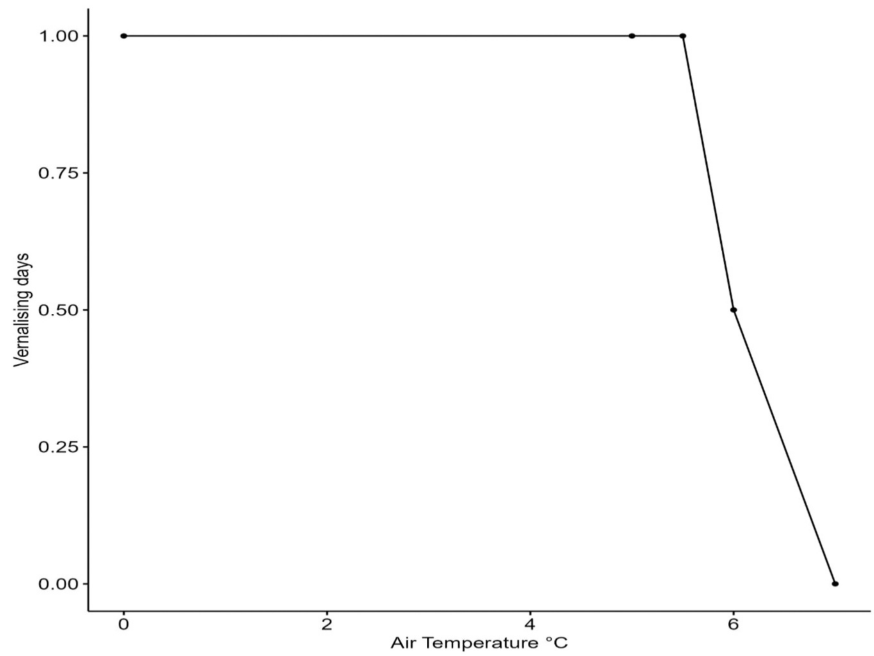

Fig. 2. The relationship between the 3 hourly average air temperature (x-axis) and the accumulation of vernalising days (y-axis).

et al., 2013). The photosynthesis parameters were adjusted during the parameterisation process, i.e., interpolations against temperature for the nitrogen factor (FN), temperature factor (FT), water factor (FW), and vapour pressure deficit factor (FVPD) were adjusted downward from the Wheat model values to account for the assumed cooler climate adaptations of intermediate wheatgrass (Allen and Ort, 2001).

2.7.2. *Canopy parameters*

The Intermediate Wheatgrass model represents all canopy leaves using the APSIM Next Generation *SimpleLeaf* model. It does not distinguish between the age and placement of the leaves. Specific Leaf Area (SLA) was set to a value of 0.03 mm^2/kg using data collected from plots of intermediate wheatgrass grown at Cowra, NSW and Pittsworth, QLD (12 plots at each location) (Innes et al., 2025a), and from previous studies, such as specific leaf area (SLA) data for *Thinopyrum ponticum* (Borrajo et al., 2018).

2.7.3. *Extinction coefficient*

Canopy development is calculated by a combination of SLA, leaf live weight, and the extinction coefficient. The extinction coefficient takes account of shading and leaf angle as the canopy develops. For intermediate wheatgrass the extinction coefficient was set to 0.5 during the vegetative stages, based on the values for the APSIM Next Generation Wheat model. This value increases as the plant develops through the

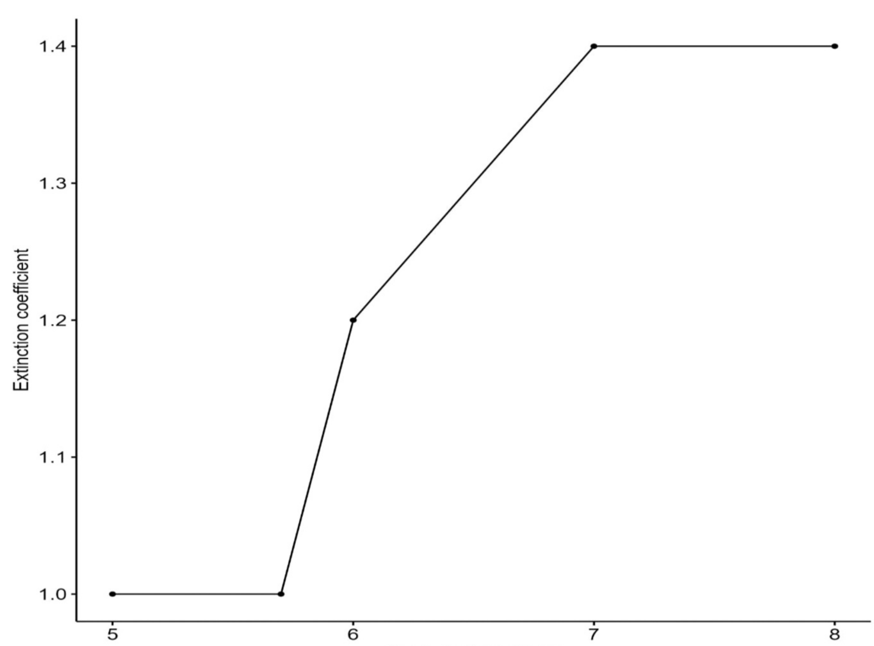

Fig. 3. Extinction coefficient value (y-axis) by phenological stage (x-axis). The initial vegetative stages (1−4) are set to a constant value of 0.5, then increasing and plateauing during the stem elongation to mature (reproductive) stages (5−9).

reproductive stages (Fig. 3), with leaves becoming more prostrate resulting in increased lower leaf shading (Campbell, 1986).

2.7.4. Leaf senescence

The senescence rate accounts for the proportion of live leaves moving to the dead pool each day. The rate was set initially to the values for the Wheat model, then adjusted to account for the Intermediate Wheatgrass model phenology stages, referencing data from Jungers et al. (2018) that indicated leaf biomass decreased quadratically as stems and inflorescences increased.

2.7.5. Biomass allocation and components

Target biomass proportions during the different phenological stages were set using information from Jungers et al. (2018), and from field experiments at Cowra, NSW and Pittsworth, QLD (Table 4).

2.7.6. N supply and concentrations

The supply to plant organs of nitrogen (N) for dry matter synthesis originates from leaf photosynthesis and uptake of N from the soil by the roots. This can be stored and then partitioned to other organs as necessary by the *Arbitrator* class, which is a sub-class of the APSIM top level *Plant* class. The N retranslocation *ReferenceRate*, *SoilMoistureFactor*, and *TemperatureFactor* used by the *Arbitrator* were initially set to the values used by the Red Clover model (Cichota, 2021).

2.8. Stem

The *Stem* generic organ was copied from the Wheat model with modifications to the senescence rate and maximum N concentration interpolations to account for the reduced number of phases in the Intermediate Wheatgrass model (n = 9), compared to the Wheat model (n = 11).

2.9. Spike

The *Spike* generic organ was copied from the Wheat model with adjustments to the stage interpolations to match the Intermediate Wheatgrass model phenology stages.

2.10. Grain

The *Grain* reproductive organ was modified from the *Grain* organ in the Wheat model. Grains per gram of stem and maximum potential grain size were set to values obtained from 16 intermediate wheatgrass plots grown at Cowra, NSW (*GrainsPerGrainOfStem*=15, *MaximumPotentialGrainSize*=0.02 g (Innes et al., 2025a)).

2.11. Root

For this implementation of the model, the *Root* organ was copied from the Wheat model without modification pending further data availability and analysis. Effective modelling of root systems is ideally based on data that describe the root system architecture, root growth, soil type interactions, soil layer interactions, root water relationships, and nutrient status (Wang and Smith, 2004). However, the root traits most important for plant function (e.g., specialised chemical or anatomical traits) are not always the ones commonly measured (Freschet et al., 2021). It is known that intermediate wheatgrass has a deeper and more dense root system than wheat (DeHaan and Ismail, 2017). Deeper roots also correlate to a higher root front velocity (Sciarresi et al., 2024). Annual cereal roots, having earlier root senescence than perennials, can result in increased decomposition and soil respiration in the initial year (Kim et al., 2022b). Perennial cereals potentially accrue more soil organic matter and carbon (partly due to reduced tillage), although analytical and experimental procedures to accurately measure this remain uncertain (Kim et al., 2022b). Daly et al. (2022) observed that root density in the upper layer was negatively associated with soil available nitrogen, which was correlated with reduced nitrous oxide emissions at some sites. This is consistent with observations of reduced nitrous oxide emissions under perennial pastures compared to periods of fallow (Li et al., 2022). Dobbratz et al. (2023) also observed that the root concentration of nitrogen in intermediate wheatgrass declined at physiological maturity. This highlights differences in N-retention/N-loss between annual and perennial crops, which may accumulate over time and need to be accounted for in future iterations of the Intermediate Wheatgrass model.

Table 4
Harvest weights, by percentage, of intermediate wheatgrass grown at Cowra, NSW and Pittsworth, QLD in Australia in 2022 (Innes et al., 2025a). Numbers in parenthesis represent the standard error of the mean.

Location	Stems %	Leaves %	Heads %
Cowra NSW	58.9 (2.85)	21.6 (1.61)	19.5 (2.99)
Pittsworth QLD	42.4 (5.23)	54.6 (5.66)	3.0 (0.59)

2.12. Statistical analysis

Parameterisation and validation results for above ground biomass, grain yield, and phenological stage using the Zadoks scale (Zadoks et al., 1974) were analysed with the predicted-observed graphing package of APSIM Next Generation. Each predicted-observed graph displays a regression equation, coefficient of determination (r^2), root mean square error (RMSE), and RMSE standard deviations ratio (RSR). The data for validation (Table 2) was collected independently from the parameterisation data and is used for the final model analysis.

2.13. Sensitivity analysis

Three groups of sensitivity analyses simulations were run to ascertain if the predictions of the Intermediate Wheatgrass model would react sensibly to management and environmental input variations. The analyses comprised: a) varied irrigation levels, b) different quantities of nitrogen fertiliser application, and c) a transect of locations from north to south in eastern Australia, representing a progression from a lower latitude, sub-tropical location (i.e., Emerald in QLD) to a cool temperate location (i.e., Ross in Tasmania). The irrigation and fertiliser simulations were completed for Cowra, NSW using corresponding weather records from 1st Jan 2006–28 th May 2009. The 2006–2009 period was chosen because it encompassed dry seasons, when irrigation was expected to increase yields. This period occurred during the 'millennial drought', an extended period of drought in southern Australia, where annual rainfall was consistently below average (630 mm) at the Cowra site and at many locations across southern Australia. The latitude simulations used weather data for the years 2015–2018 from each respective locality. These years encompassed a period with generally no large rainfall excesses or deficits on the east coast of Australia, so that the model was simulating responses to daylength and temperature changes as far as possible. A soil close to the simulation location was selected from the APSIM Next Generation download soils feature, ISRIC SoilGrids (de Sousa et al., 2020), for each simulation.

3. Results

3.1. Parameterisation and calibration

The phenology parameterisation and calibration, using the datasets in Table 1, had a small over-prediction trend in the later phenology stages (regression line slope 0.88 (Fig. 4)). The grain yield parameterisation and calibration resulted in a higher standardised RMSE (RSR=0.83) and lower r^2 (0.60) compared to the phenology (RSR = 0.23 and r^2 = 0.90) (Fig. 4). This may be explained by the less complex

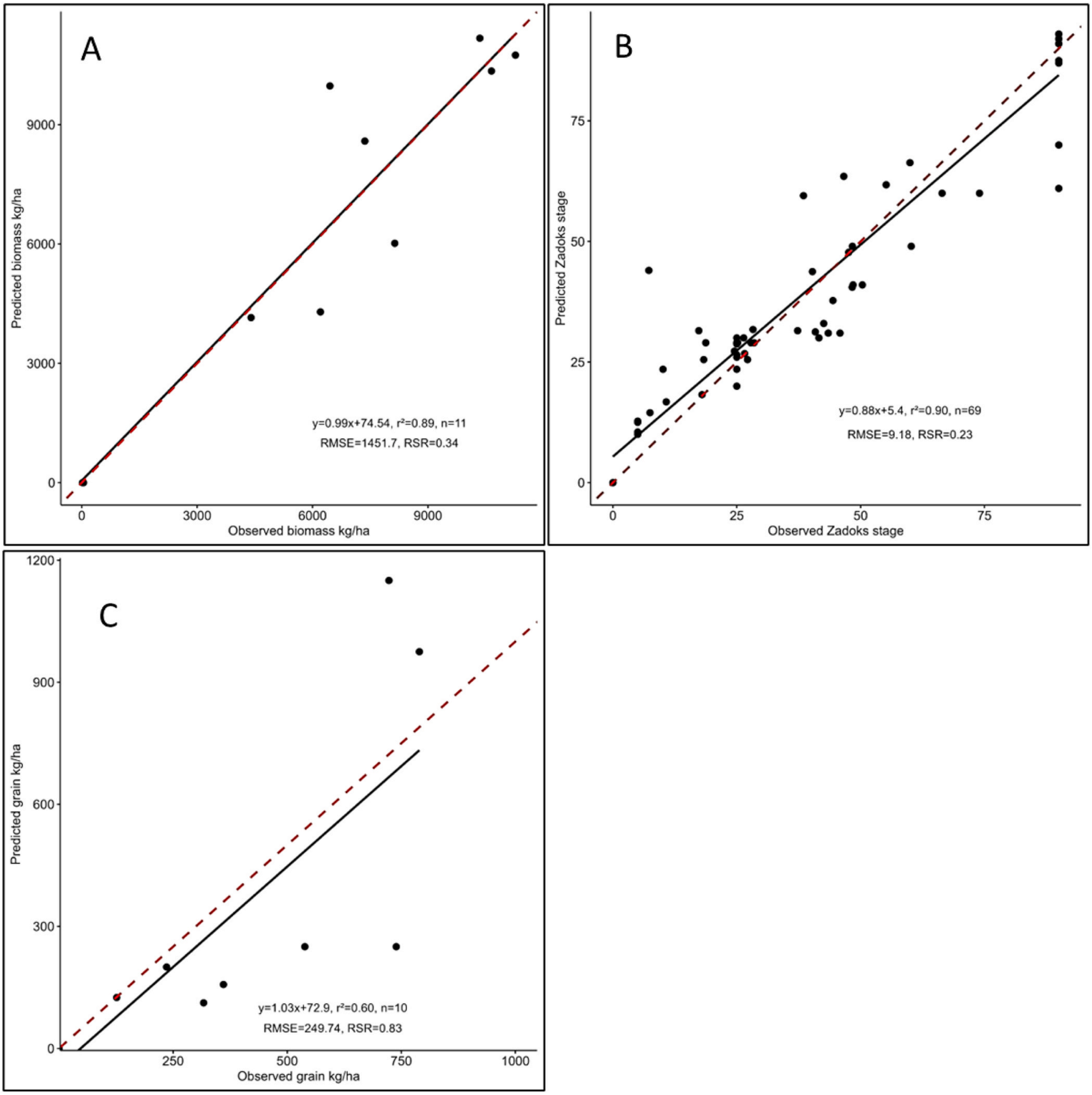

Fig. 4. Parameterisation dataset (Table 1) simulation results comparisons after calibration. Predicted vs. observed regressions for (A) biomass kg/ha (B) Zadoks growth stage (C) grain kg/ha. The black solid line represents the fitted linear regression of the parameterisation data. The red dashed line is 1:1.

modelling required to predict phenology, compared to yields, and that the phenology datasets had multiple observation points per experiment, while yield observations were fewer, being generally completed at grain harvest.

3.2. Validation

Validation simulations were completed using the datasets in Table 2. The phenological predicted vs. observed (Fig. 5) showed a good fit ($r^2 = 0.96$, RMSE = 7.94), with the slope indicating a slight over-prediction of phenology progress. The biomass and grain yield predicted vs. observed generated a regression line slope close to a value of 1.0. The spread of points, reflected by the RMSE's of 2372 kg/ha and 148 kg/ha for biomass and grain yield respectively, are within the range of errors reported for the data compiled from the literature and experimental studies. The validation datasets are results from field sample plots of varying size (Table 2) that have been extrapolated to a standard kg/ha to compare with the predictions of the model. This scaling has not created any obvious issues.

3.3. Sensitivity analyses

3.3.1. Irrigation

Irrigation sensitivity was tested using levels of a) zero, b) 30 mm on the 24th of each month, and c) 15 mm four times a month. Nitrogen fertiliser rate was 40 kg/ha annually in May. Grain in the first 'drought

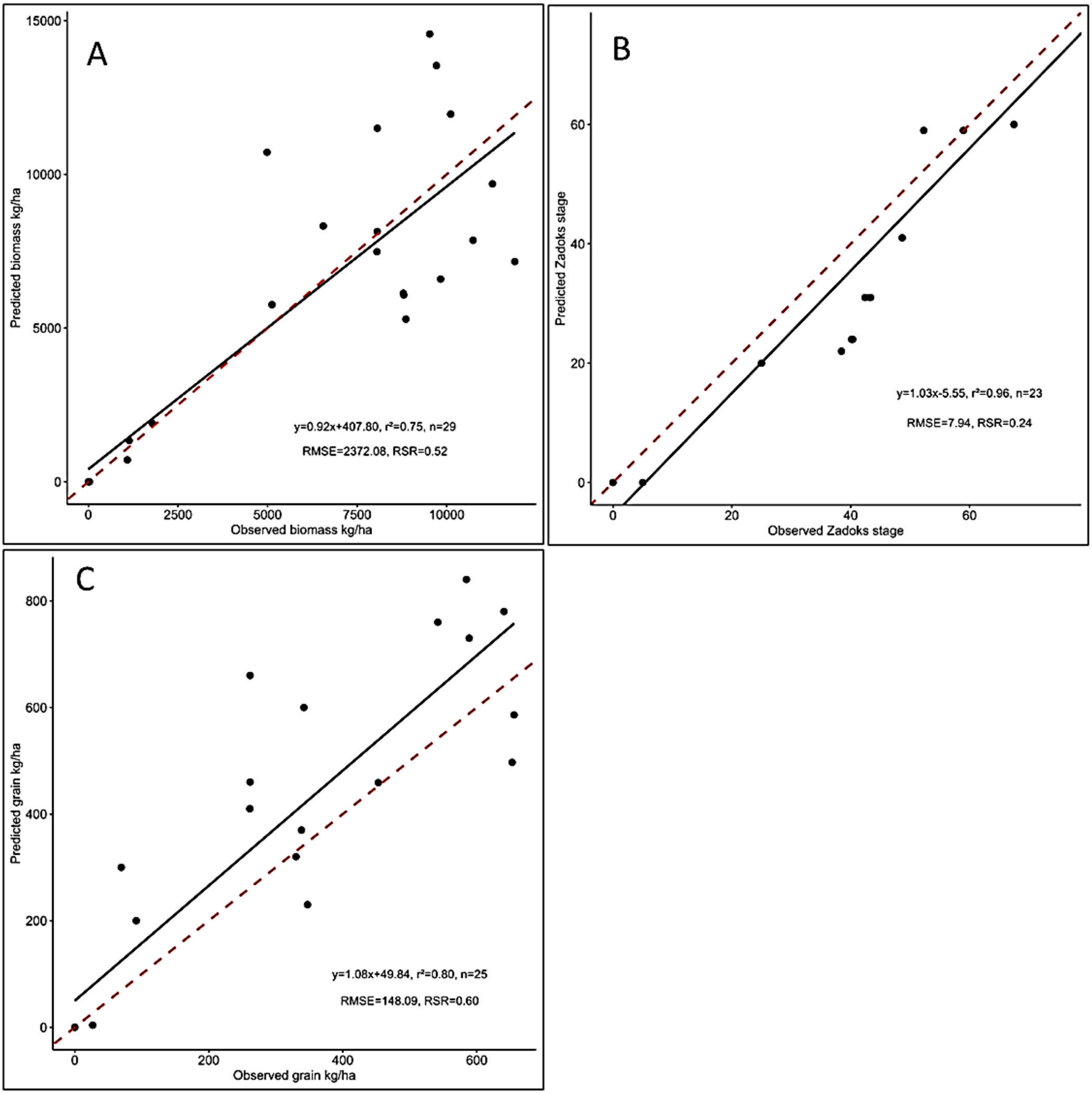

Fig. 5. Validation dataset (Table 2) simulation results comparisons. Predicted vs. observed regressions for (A) biomass kg/ha (B) Zadoks growth stage (C) grain kg/ha. The black solid line represents the fitted linear regression of the validation data. The red dashed line is 1:1.

year' was only produced under high irrigation (Table 5).

3.3.2. Fertiliser

Nitrogen (N) fertiliser sensitivity simulations were parameterised using three levels: a) no N fertiliser application, b) nitrogen 50 kg/ha applied annually in May (Autumn), and c) nitrogen 150 kg/ha applied annually in May. Irrigation for the fertiliser simulations was 130 mm, applied bi-monthly. Simulated biomass responses increased as fertiliser application increased. Simulated grain yield response to increasing fertiliser was mainly evident in year 3 (Table 6).

3.3.3. Latitude

In the latitude sensitivity tests, the simulated stem elongation dates

Table 5
Irrigation sensitivity: predicted yields for different rates of irrigation. Simulated location was Cowra NSW, Australia with sowing date 22nd May 2006. Total Cowra rainfall 2006 = 271 mm, 2007 = 496 mm, 2008 = 511 mm.

Irrigation	Predicted max. biomass kg/ha			Predicted grain kg/ha		
mm per year	2006	2007	2008	2006	2007	2008
0	521	412	1093	0	0	0
360	5519	4875	3213	0	86	14
720	5206	5365	6731	50	41	199

decreased from the 22nd Oct in Dalby QLD to the 9th Oct in Ross Tasmania (Table 7). The simulation in Emerald QLD (the most northern latitude) did not reach reproductive stage in any of the years. In Dalby QLD (the next most northern latitude) reproductive stage was only achieved in one of the three years, and in two of the three years in Tamworth NSW (the third most northern latitude). In the more southern latitudes, (Bathurst NSW, Hamilton Vic, Ross Tasmania) grain was produced in each of the three years. Grain maturity dates were generally later at the more southern (higher latitude) locations.

4. Discussion

The Intermediate Wheatgrass model validation predicted phenology, biomass, and grain yields with RMSE values of 7.94 (Zadoks scale), 2372 kg/ha, and 148 kg/ha respectively. The phenology validation RMSE is comparable to the results achieved by Duchene et al. (2021) (RMSE=7.8 using the BBCH scale (Hess et al., 1997)), and the APSIM Next Generation Wheat model Brown et al. (2018) (RMSE=1.08 using the Haun scale (Haun, 1973)). The range of yield RMSE values for the Intermediate Wheatgrass model are also within the range reported by Brown et al. (2018) for the combined validations of the APSIM Next Generation Wheat model (above-ground weight RMSE=2022 kg/ha, harvested grain RMSE=1004 kg/ha). The model simulation results (from parameterisation, validation, and sensitivity) reveal a close correlation between latitude and reproductive triggers. The timing of the transition to reproduction (stem elongation stage), at the locations at which it occurred, was consistent at any given latitude, regardless of management actions and soil type. The model predictions were consistent with accounts in the literature that the timing of reproductive development of many cool climate grasses, including intermediate wheatgrass, is closely related to vernalisation requirements (Heide, 1994; Innes et al., 2025b). It has been noted by other researchers that, for intermediate wheatgrass, the time to accumulate the chilling hours to achieve vernalisation, and the subsequent timing of secondary induction, can be better predictors of phenology progression than thermal time (Barriball et al., 2022; Duchene et al., 2021; Ivancic et al., 2021). An important aspect of the Intermediate Wheatgrass model, therefore, is that it accurately predicted the likely transition of intermediate wheatgrass from vegetative to reproductive stage. With this knowledge, geographical zones where grain production may be viable can be determined.

Biomass and grain yield simulation predictions had lower predicted-observed coefficient of determination values than those for phenology, both in the parameterisation and validation results (Fig. 4 and Fig. 5). This may be an indication of the increased complexity in modelling biomass and grain yields compared to phenology (e.g., sensitivity results for irrigation and fertiliser, Table 5 and Table 6), and/or possibly management actions were not accurately or completely captured in the parameterisation or validation processes. The parameterisation and validation processes assumed a standard intermediate wheatgrass genotype, while the datasets comprised differing intermediate wheatgrass genotypes. The potential genotypic variability among these materials were not accounted for and could have influenced the alignment between the predicted and observed values.

Biomass yields responded to irrigation levels in a sensible way, with the largest difference in predicted biomass being between no-irrigation and low-irrigation occurring after the dry year in 2006 (Table 5). Grain yield response was not as pronounced for the same period. Zhen et al. (2024), in their review of intermediate wheatgrass management, noted that high vapour pressure deficits had a greater effect on grain yields than precipitation. In a comparison of annual rye and hybrid perennial rye crops, higher vapour pressure deficits and higher evapotranspiration were observed in perennial crops (relative to annual crops) when encountering drier conditions early in the growing season (Kim et al., 2022a). This may partly explain the predicted zero grain yield (Table 5) under moderate irrigation in 2006 (the driest year). The overall water use efficiency of perennial crops, however, was observed to be similar to that of the annual crops when measured over multiple years (Kim et al., 2022a). In the Intermediate Wheatgrass model, vapour pressure deficit, along with water availability and other environmental variables, modify the rate of photosynthesis, and thus the assimilates available for grain production, possibly leading to the lower predicted grain response.

The drought conditions during the simulation period (2006–2008) may also have reduced the grain yield predictions. Although irrigation may have alleviated the water deficit, it would have had little effect on other climatic parameters that may impact grain yield, such as temperature. Nevertheless, early generation intermediate wheatgrass perennial grain genotypes have a relatively low grain yield potential compared to annual wheat, so a large grain yield response to irrigation was perhaps not to be expected.

Biomass increased in line with N fertiliser application rates in the simulations. Grain yields showed a small response in year one and two, but there was a higher response in year three (Table 6). The grain yield simulation result agreed with the field responses observed by Fernandez et al. (2020). However, Jungers et al. (2017) reported a decrease in grain yields in the third year in response to high levels of N fertiliser. They attributed this grain yield reduction to higher levels of lodging under the higher fertilisation regime, which affected pollination and grain development. The effects of possible lodging have not been considered in this version of the model. Another factor affecting yields, associated with higher fertilisation levels, is potential for increased weed competition (Locatelli et al., 2023). This also was not considered in this version of the model.

Latitude simulations had a strong influence on whether any grain would be produced (Table 7). Intermediate wheatgrass has high vernalisation threshold compared to crops such as annual wheat (Innes et al., 2025b). Field experiments (Innes et al., 2025a; Locatelli et al., 2023) have produced low to zero grain yields in lower latitudes (with sub-tropical climates). The model appears to capture this aspect, with an occasional higher grain yield possible, depending on seasonal conditions.

The sensitivity simulations, which were based on Australian locations, predicted relatively low grain yields (typically 100–300 kg/ha) compared to experimental results both from North America, averages 200–600 kg/ha (e.g., Hunter et al. 2020a, Pugliese et al. 2019, Jungers et al. 2022), and Cowra, NSW Australia, 300–550 kg/ha (Hayes et al., 2018). This may be due to a combination of factors, such as the genotype modelled and the years chosen for simulation. Soil factors are also an important consideration when setting up a simulation. It was found that a change in the value of the soil organic carbon content parameter (e.g., from 0.85 % to 2.5 %) had a significant effect (up to 150 % increase) on grain yield predictions. Soil pH (>6.6) has also been associated with higher grain yields (Hayes et al., 2018). Intermediate wheatgrass has a deeper and more dense rooting structure than annual wheat (Duchene et al., 2020), which has implications for how growth and yields will be affected by periods of heat and/or moisture deficits. How the plant interacts with different soil types, such as light or dense soil structures (Wang and Smith, 2004) may also be important when modelling growth in areas with lighter-textured soils (e.g., some temperate areas of Australia). Considering these implications, the root organ modelling aspect of the current Intermediate Wheatgrass model requires further

Table 6
Fertiliser sensitivity: predicted yields for different rates of fertiliser application with bimonthly irrigation. Simulated location was Cowra, NSW Australia, with sowing date 22nd May 2006.

Fertiliser	Predicted max. biomass kg/ha			Predicted grain kg/ha		
N kg/ha	2006	2007	2008	2006	2007	2008
0	2905	3911	3472	36	54	95
50	3143	4980	5190	57	57	161
150	3988	7005	8446	58	83	312

Table 7
Sensitivity to latitude (years 2015–2017): Predicted phenology stages and grain yields using simulated locations in a transect from Emerald QLD to Ross Tasmania. All simulated sowing dates were 22nd May 2015.

	Zadoks stage 31 (stem elongation) date			Zadoks stage 92 (grain maturity) date			Grain yield kg/ha		
	2015	2016	2017	2015	2016	2017	2015	2016	2017
Emerald Lat.−23.52 Lon.148.16	na*	na*	na*	na*	na*	na*	na*	na*	na*
Dalby Lat.−27.18, Lon.151.26	22nd Oct 2015	21st Oct 2016	22nd Oct 2017	na*	na*	20th Jan 2018	na*	na*	1029
Tamworth Lat. −31.09 Lon.150.93	18th Oct 2015	17th Oct 2016	18th Oct 2017	20th Jan 2016	9th Jan 2017	na*	83	na*	242
Bathurst Lat. −33.41 Lon.149.58	16th Oct 2015	15th Oct 2016	16th Oct 2017	8th Jan 2016	10th Jan 2017	11th Jan 2018	41	16	30
Hamilton Lat. −37.74 Lon.142.02	12 Oct 2015	11th Oct 2016	12th Oct 2017	18th Feb 2016	19th Jan 2017	18th Jan 2018	96	69	232
Ross Lat. −42.03 Lon.147.49	9th Oct 2015	8th Oct 2016	9th Oct 2017	21st Feb 2016	23rd Jan 2017	24th Jan 2018	30	19	71

na* stage not achieved

development.

The following constraints and deficiencies have been identified for the current version of the Intermediate Wheatgrass model:

- It was assumed that crop rows remain separate, with no recruitment from seed or rhizomes between rows.
- Defoliation and harvesting removes biomass from the field, rather than being partially returned (as may be the case with grazing livestock).
- Parameterisation and validation relied heavily of experimental results from higher latitude regions, thus yield predictions may be questionable for lower latitude temperate and sub-tropical regions. This may continue to be the case until genotypes that successfully vernalise at lower (e.g., sub-tropical) latitudes are developed. However, phenological predictions of the model are considered sound for both high and low latitudes.
- While the model was developed using experimental growth data from a variety of genotypes (as the volume of data prevented genotype specific development), no attempt has been made to model individual genotypes.
- Root growth and root biomass were not modelled specifically for intermediate wheatgrass; the APSIM Next Generation Wheat (Brown et al., 2018) *Root* model was used unaltered. As more data become available the *Root* organ parameters could be modified to reflect the deeper rooting structure and greater retention of soil nitrogen in intermediate wheatgrass (e.g., Duchene et al., 2020).

Despite these deficiencies, the Intermediate Wheatgrass model is unique in that it accurately predicts phenology, while also reasonably predicting biomass yields, grain yields, and management responses over a period of multiple years. It provides a sound basis for further model development and application.

5. Conclusion

The Intermediate Wheatgrass model is an important step in the ongoing development and establishment of perennial grains crops in Australia and worldwide. It is the only comprehensive model that predicts the phenology, biomass yield, grain yield, and management responses of an intermediate wheatgrass crop, and as such provides a vital tool for plant breeders and farm planners. A strength of the model is its ability to predict phenology (r^2=0.96). The model can help delineate the latitudinal and climatic boundaries of grain production, using existing genotypes, saving valuable time and resources that may be utilised in other areas of perennial cereals research. Initial modelling indicates that currently available intermediate wheatgrass material is likely to be restricted to higher latitude locations, without further breeding to lessen its vernalisation and photoperiod requirements. The model also reacts sensibly to variation in management inputs including irrigation, N fertiliser, and latitude. Future development of the model should include additional intermediate wheatgrass genotypes, to account for the ongoing breeding effort on this species (Bajgain et al., 2022). There is also a need to include root modelling that is appropriate to the deeper root systems of perennial cereals, as well as the inter-row multi-year growth resulting from seedling recruitment and growth from rhizomes. Future models could also include other candidate perennial cereals, such as mountain rye, or perennial rice.

CRediT authorship contribution statement

Innes Peter Joseph: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **M.T. Newell:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **A.M. Radanielson:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **R.C. Hayes:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **K.G. Pembleton:** Writing – review & editing, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Peter Innes reports financial support was provided by University of Southern Queensland. Peter Innes reports a relationship with University of Southern Queensland that includes: funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplemental material

None

Data availability

Data will be made available on request.

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