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Sensitivity of a crop growth simulation model to variation in LAI and canopy nitrogen used for run-time calibration

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ABSTRACT

Run-time calibration, i.e. adjusting simulation results for field observations of model driving variables during run-time, may allow correcting for deviations between complex mechanistic simulation model results and actual field conditions. Leaf area index (LAI) and canopy nitrogen contents (LeafNWt) are the most important driving variables for these models, as they govern light interception and photosynthetic production capacity of the crop. Remote sensing may provide (spatial) data from which such information can be estimated. How, when and at what frequency such additional information is integrated in the simulation process may have various effects on the simulations. The objective of this study was to quantify the effects of different run-time calibration scenarios for final grain yield (FGY) simulations in order to optimize remote sensing image (RS) acquisition. The *PlantSys* model was calibrated on LAI and LeafNWt for maize in France and used to simulate maize crop growth in the Argentina and the USA, for which non-destructive estimates of LAI and leaf chlorophyll contents were acquired by optical measurement techniques. Leaf chlorophyll data were used to estimate LeafNWt. Due to its structure, the *PlantSys* model was more susceptible to run-time calibration with LeafNWt than with LAI. Run-time calibration with LAI showed the largest effect on FGY before and around flowering, and could mainly be related to maintenance respiration costs. Run-time calibration with LeafNWt showed the largest effect on FGY at and after flowering and could mainly be related to the change in effective radiation interception due to change in leaf life. The accuracy of LAI estimates showed a major effect on FGY for underestimations but was small in absolute sense. The accuracy of LeafNWt estimates had significant impact at all crop development stages, but was the strongest after flowering where crop growth and nitrogen uptake are less able to recuperate from changes in LeafNWt. In absolute sense, the effect on FGY was as strong as the accuracy of the LeafNWt estimates when applied in the early reproductive stages. Based on these results it was concluded that remotely sensed in-field variability of LAI and LeafNWt is valuable information that can be used to spatially differentiate model simulations. Run-time calibration at sub-field level may lead to more accurate simulation results for whole fields.

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1. Introduction

Complex mechanistic crop growth simulation models are highly data-demanding and have to be calibrated locally to give accurate and reliable simulation results. Even if these requirements are met, simulation results may deviate from actual field observations for a variety of reasons. Especially when input data are difficult to measure accurately or expensive and laborious to collect, they are easily replaced by expert knowledge, inter- or extrapolated data and/or approximations that give reasonable simulation results, but may still deviate from actual field conditions. Run-time calibration, i.e. adjusting simulation results on the basis of field observations of model driving variables during simulation, allows corrections of such deviations. Such additional information about the crop–soil system may come from classical field sampling methods, or may be derived from other techniques, such as remote sensing observations that would also directly reveal in-field variability of certain crop and soil characteristics in one overview. With a variable degree of success and at different spatial resolutions, remote sensing has been used to estimate crop and soil characteristics (Thenkabail et al., 2000), such as leaf area index (Clevers, 1989; Bouman, 1992), biomass (Turner et al., 2002), chlorophyll contents (Ma et al., 1996; Jago et al., 1999; Jongschaap and Booij, 2004), and evapotranspiration (Bastiaanssen et al., 2000). Best results are described for hyper-spectral imagery, however, these data are not always available, or are too expensive for use at high temporal resolution. Vegetation indices are often derived from observations in the visible domain and for satellite and airborne platforms cloud cover may interfere. Furthermore, high resolution and hyperspectral satellite sensors may have a low overpass frequency, further reducing the chance of obtaining images of the desired objects at regular intervals. Cloud cover is a minor problem for airborne observations that can take place upon request, but frequent flights may be restricted by environmental regulations.

Observation frequency, interval, timing and accuracy of the data used in run-time calibration influence simulation results differentially. The objective of this study was to quantify the effects of different run-time calibration scenarios on simulated final grain yield (FGY), to support optimization of remote sensing image acquisition and for predicting the effects of sub-optimal run-time calibration sets.

Run-time calibration was performed with the *PlantSys* simulation model (Jongschaap, 1996; Jongschaap et al., 2002), applying five sequential optical sensing estimates (RS) in the course of the growing season of leaf area index (LAI) and leaf chlorophyll content. Leaf chlorophyll contents were used to calculate canopy nitrogen contents (LeafNWt). *PlantSys* was calibrated for maize growth in France (Jongschaap et al., 2002) and used for maize growth simulations in Argentina and the USA, for which estimates of LAI and leaf chlorophyll were acquired by non-destructive optical measurements techniques. The effects were analyzed of number of integrated RS observations (1–5) for run-time calibration, as well as their timing in the growing season, and of estimation accuracy of the input variables (95, 90, 75 and 60%) for run-time calibration on simulated FGYs.

2. Materials and methods

2.1. Field experiments

For model calibration, a field experiment with maize (*Zea mays* L.) was executed in 1999 at Avignon-Montfavet, France at 43°57′N and 4°5′E. Fertilizer (15-15-15) at 500 kg ha^{-1} was applied on 13 March 1999 (DoY 72), i.e. 75 kg ha^{-1} of the elements N, P and K. Variety DK-604 was sown at 0.8 m between rows (oriented north–south) and 0.115 m between plants on 10 May 1999 (DoY 130) and emerged at a density of 9.32 plants m^{-2}. In June and July 1999 the maize was irrigated (at a rate of 20 mm) once a week and in August 1999 twice a week to restrict growth reduction due to drought stress. Plants were sampled every 5–7 days (18 times between 27 May and 7 October 1999) for determination of fresh and dry weight of leaves, stems and grains. Leaf area index (m^2 m^{-2}) was recorded just before sampling with LAI-2000 equipment (LI-COR Inc., USA). SPAD-meter (Minolta, USA) readings were taken on June 28 (DoY 178), July 23 (DoY 206) and September 16 (DoY 269). A SPAD-meter records leaf transmittance of an induced light beam in two wavelengths (±430 and ±750 nm). A direct relation between SPAD-meter readings and leaf nitrogen contents (LeafNWt, kg ha^{-1} leaf) was used (Eq. (1); $r^2 = 0.92$; Blackmer et al., 1994).

$$\text{LeafNWt} = -1.0244 + 0.0469\text{SPAD} \quad (1)$$

Additional experimental data were retrieved from maize experiments, originally designed to relate remote sensing observations to field observations, carried out under similar settings in 1997 and 1998 in ‘Blue Earth’ Minnesota (43°45′N, 94°16′W) in the USA, and in Pergamino (34°07′S, 60°09′W) and Pehuaro (36°09′S, 62°58′W) in Argentina. From these trials, information was available on planting and harvest dates, maize cultivars, fertilizer application (dates and rates), irrigation (dates and rates), and some information on soil characteristics. These data are further referred to as the ‘EU Croma database’, named after the project through which these data were made available (Croma, 2002).

Five experimental sites from ‘Blue Earth’ (BLE), eight sites from Pergamino (PG) and six sites from Pehuaro (PH) provided data on leaf area index and chlorophyll contents at different crop development stages. Leaf SPAD measurements (Minolta) were related to leaf chlorophyll contents (LeafChl; μmol m^{-2} leaf; Eq. (2); $r^2 = 0.96$; Markwell et al., 1995) and then converted to leaf nitrogen contents (LeafNWt, kg ha^{-1} leaf; Eq. (3); $r^2 = 0.83$; Ercoli et al., 1993). This two-step approach was needed because original SPAD values were no longer available in the EU Croma database. As a result, LeafNWt estimates may have been less accurate than LeafNWt estimates in the Avignon dataset.

$$\text{LeafChl} = 10^{\text{SPAD}^{0.265}} \quad (2)$$

$$\text{LeafNWt} = -2.797 + 0.0188\text{LeafChl} \quad (3)$$

In this study, average values and standard deviations per plot and per observation date were generated. To study the