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Long-term simulation of soil–crop interactions in semiarid southwestern Saskatchewan, Canada

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Abstract

Water and nutrient dynamics of soils are strongly related to land use and crop biomass production. Selected treatments of a long-term field experiment, established in 1967 at Swift Current in southwestern Saskatchewan, Canada with different crop rotations were simulated over a period of 25 years using the integrated soil–crop model HERMES. Results of two rotations (continuous wheat and fallow–wheat) were compared in terms of crop biomass and grain yield production, water and nitrogen dynamics and nitrogen losses by leaching and denitrification. Model performance was analysed by comparing the simulated state variables in soil and crops to measured data. The model simulated crop biomass, grain yields and nitrogen uptake well, with coefficients of determination (r^2) of 0.88^{***}, 0.70^{***} and 0.71^{***}, respectively. Soil water content during the growing season was simulated well with r^2 of 0.80^{***}; however, simulating soil water dynamics during the winter period was problematic. This was due, at least in part, to the model's inability to estimate surface runoff, which occurred during periods of snowmelt when the soil was still frozen. Especially the performance of the crop yield estimation dropped down significantly without re-initialisation of water contents in spring. Although simulated soil mineral nitrogen content was mostly within the standard deviation of the replicate measurements, the very high variability of the measurements resulted in small correlations between simulation and observations ($r^2 = 0.22^{***}$). To reflect the trends of soil organic nitrogen, it was necessary to consider the historical management starting the model in 1910.

Keywords: Crop rotation; Water dynamics; Nitrogen dynamics; Above-ground biomass; Yield; Nitrate leaching

1. Introduction

Water and nutrient dynamics of soils are strongly related to land use and crop biomass production. Site conditions (e.g., soil properties and local weather conditions) are the main boundary conditions that dictate and constrain land use and management practices as they influence the quantity and quality of water resources. Agro-ecosystem models are being more frequently used for site specific analysis and the development of site adapted agricultural production systems (Smit et al., 2000; Hupet and Vanclooster, 2002; Kersebaum et al., 2003a). On a regional and/or national scale they are used for the evaluation of current land use and potential remediation measures through scenario simulations (see e.g., Børgesen et al., 2001; Heineman et al., 2002; Kiniry et al., 2002; Kersebaum et al., 2003b). Validation, and if necessary adoption of the models, should be done using independently measured data from field experiments, especially if they are applied for site conditions beyond which they were developed. The present study was therefore aimed at investigating the capability of the model HERMES (Kersebaum, 1995), which was developed for sub-humid agricultural conditions in Central Europe, to simulate soil–crop interactions over a period of 25 years under the semiarid climatic conditions of the Canadian prairies.

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2. Material and methods

2.1. The experimental site

The data used for the simulations were collected from a field experiment that was established in 1967 at the Semiarid Prairie Agricultural Research Centre (SPARC) in Swift Current, Saskatchewan, Canada. Swift Current (50° 17′N, 107° 48′W, elevation 883 m) is located in the driest portion of the Canadian prairies—the Brown Chernozemic soil zone with long cold winters and short growing seasons (Pelton et al., 1967). The soils are frozen from mid-October until March/April with a mean maximum frost depth of 150 cm (Edey and Joynt, 1975). Water availability is the main factor limiting crop growth in the semi-arid prairies, i.e., the Brown and Dark Brown soil zones. Rainfall is marginal for many agricultural activities (on average, 167 mm during May, June and July) and timing of rain is as important as the total amount (Campbell et al., 1990). The mean annual precipitation varies between 350 and 375 mm; in contrast the annual potential evapotranspiration was calculated to be 729 mm (Campbell et al., 1983). The landscape is a slight hummocky terrain.

Details of the design and management of the Swift Current long-term crop rotation study have been reported previously (Campbell et al., 1983, 2004; Zentner and Campbell, 1988; Campbell and Zentner, 1993); consequently, only a review pertinent to this study will be presented.

The rotation study was located on a Swinton loam (Ayres et al., 1985), an Orthic Brown Chernozem (Canada Soil Survey Committee on Soil Classification, 1978). The pH (water paste) of the top 15 cm of soil was 6.5 and the water table is located beyond 10 m. The land was slightly sloping (<3%) and had been cropped previously to a fallow-spring wheat rotation, receiving minimal fertilizer since 1922.

Twelve crop rotation-fertility treatments, considered potentially suitable for south-western Saskatchewan, were established in 1967 on 81 plots (0.04 ha each) in a randomised complete-block design with three replicates. All phases of each rotation were present every year. Two treatments, each receiving recommended rates of N and P fertilizer (see below), were selected to evaluate the HERMES model: continuous wheat (CW) and a fallow–wheat rotation, which will be described as fallow–wheat (FW) for the fallow phase and wheat–fallow (WF) for the wheat phase. This enables us to compare wheat growth phases between the two rotation systems in each year.

Seedbed preparation, herbicide application, seeding, harvesting, and tillage operations were reported previously (Campbell et al., 1983, 1992; Zentner and Campbell, 1988). Spring wheat was generally seeded in early May and the plots were harvested at the full ripe stage, usually in late August to mid-September. Commercial farm equipment was used to perform all cultural and tillage operations. Weed control was achieved by a combination of mechanical tillage and herbicides using recommended methods and rates (University of Saskatchewan, 1975). In the fall, after harvest, 2,4-D was applied to all plots to control winter annual weeds. On average, summer fallow plots received about four shallow tillage operations.

During the first 18 years of the study soil sampling took place eight times each year; prior to seeding and at the following growth stages: emergence, three-leaf, five-leaf, shot blade, dough, full ripe (harvest) and after harvest in mid-October. Triplicate soil samples were taken from the 0–15, 15–30, 30–60, 60–90 and 90–120 cm depths. These samples were analysed for NO_3–N (Hamm et al., 1970), exchangeable NH_4–N (O'Brien and Fiore, 1962), and gravimetric soil water content.

Analysis of total (organic) N in the soil was described in detail by Campbell and Zentner (1993). Two soil samples were taken from the 0–15 and 15–30 cm depths within the central part of each plot. Samples were taken in spring 1976, in fall 1981, in 1984 (some in fall and some in spring 1985) and in fall 1990, but no samples were taken in 1967. The soil was air dried, sieved (<2 mm) and ground to <1 mm. Small pieces of crop residues passing through the 2-mm sieve were regarded as soil organic matter. Total soil N concentration was measured by Kjeldahl analysis (Atkinson et al., 1958) and these concentrations were converted to a weighed basis using bulk densities of 1.22 and 1.30 Mg m^{-3} for the 0–15 and 15–30 cm depths, respectively.

Fertilizer N, as NH_4NO_3 was applied (broadcast in spring) based on levels of soil NO_3–N (0–0.6 m depth) measured in individual plots in the previous fall. From 1967 to 1989 we used N rates as recommended by the soil testing laboratory of the University of Saskatchewan (Saskatchewan Agriculture, 1985) to bring the total mineral N (soil test + fertilizer N) level to 65 kg ha^{-1} (normal moisture conditions assumed). In 1990 the soil testing laboratory recommendations for N were increased to 90 kg ha^{-1} of total N for wheat grown on fallow and to 73 kg ha^{-1} for wheat grown on stubble. Phosphorus fertilizer (monoammonium phosphate) was applied at a rate of 9–10 kg P ha^{-1} $year^{-1}$ with the seed in accordance with the general recommendations for the area and crop (University of Saskatchewan, 1975). Wheat grown on fallow received about 8 kg N ha^{-1} $year^{-1}$ up to 1991 and, since then about 41 kg N ha^{-1} $year^{-1}$ partly due to the more favourable growing season weather conditions during the last 7 years and partly to the new fertilizer guidelines since 1990. On average, wheat grown stubble received about 10–32 kg N ha^{-1} $year^{-1}$ in the first 18 years, and about 50 kg N ha^{-1} $year^{-1}$ in the last 7 years.

Yields were measured by cutting a swath 5 m wide and 40 m long through the middle of the cropped plots and the grain harvested with a conventional combine. The straw was distributed on the plots with a paddle-type spreader attachment on the combine and not soil-incorporated until the following spring or early summer. Small areas (2.32 m^2) were hand harvested at the full ripe stage, and until 1984 at the three-leaf, five-leaf, shot blade and dough stage, to determine above-ground plant biomass and N concentration in the grain and straw (Starr and Smith, 1978).

Meteorological parameters including daily precipitation, maximum and minimum temperatures and global radiation were assumed to be similar to those recorded at a meteorological site located 1 km west of the test site. Latent evaporation was calculated using the Baier and Robertson (1965) formula I and converted to potential evapotranspiration by using a conversion factor of 0.086 (Baier, 1971).