

RESEARCH ARTICLE

# Using a systems modeling approach to improve soil management and soil quality

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**Abstract** Soils provide the structural support, water and nutrients for plants in nature and are considered to be the foundation of agriculture production. Improving soil quality and soil health has been advocated as the goal of soil management toward sustainable agricultural intensification. There have been renewed efforts to define and quantify soil quality and soil health but establishing a consensus on the key indicators remains difficult. It is argued that such difficulties are due to the former ways of thinking in soil management which largely focus on soil properties alone. A systems approach that treats soils as a key component of agricultural production systems is promoted. It is argued that soil quality must be quantified in terms of crop productivity and impacts on ecosystems services that are also strongly driven by climate and management interventions. A systems modeling approach captures the interactions among climate, soil, crops and management, and their impacts on system performance, thus helping to quantify the value and quality of soils. Here, three examples are presented to demonstrate this. In this systems context, soil management must be an integral part of systems management practices that also include managing the crops and cropping systems under specific climatic conditions, with cognizance of future climate change.

**Keywords** APSIM, available water capacity, nitrogen management, soil functional properties, soil health, soil-plant modeling

## 1 Introduction

Soils have long been recognized as a limited and nonrenewable resource for crop growth and agricultural production<sup>[1]</sup>. *Soil quality* and *soil health* have been increasingly used as the goals in soil management. Soil

health is defined in soil management with the view that soil is a living system, and then soil quality and health are defined as the capacity of soil to sustain plant and animal productivity, to maintain or enhance water and air quality, and to promote plant and animal health<sup>[2]</sup>. The aim of good management practices is to improve soil quality and health, and this contributes to food security and agricultural sustainability<sup>[2]</sup>. Although there have been renewed efforts to define and quantify soil quality and soil health<sup>[3,4]</sup>, establishing a consensus about key indicators remains difficult<sup>[5]</sup>. Common approaches using a list of soil attributes to define a soil quality index<sup>[3–5]</sup> remain complex, often qualitative, not directly aligned with management goals (such as crop yields) and farm logistics, and difficult to use.

Soil and climate interact to determine the key characteristics of environmental conditions for crop growth and agricultural production. Soils with similar biophysical attributes will have different impacts on crop growth and yield as well as environmental processes (e.g., drainage and leaching) across contrasting climatic regions. For example, soils with the same water holding capacity may result in different crop yields under different climatic regimes<sup>[6,7]</sup>. Agricultural management practices modify the system by changing the crops and cropping systems and by modifying the biophysical conditions of soils through irrigation, fertilizer applications, soil amendments and residue management, and this helps to increase crop productivity<sup>[8,9]</sup>. In turn, these modifications change the environmental impact of production systems<sup>[10,11]</sup>.

In the soil-plant-climate context, the capacity of a soil to function may be defined based on soil attributes (e.g., water holding capacity based on soil texture). Its actual function or value of contribution to productivity and environmental outcomes depends on the type of climate, cropping system and management interventions. Soils cannot be moved to a different climate, and soil management therefore needs to be adapted to prevailing climatic conditions and for a specified goal, whether for crop production or conservation purposes. If soil quality needs

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to be quantitatively defined, the value of soils in contributing to crop production or environmental sustainability can only be quantified in such a systems context. Without the use of this framework, soils can become irrelevant even to crop production. The increasing development of soil-free crop production systems, such as hydroponics, is a good example<sup>[12–14]</sup>.

Soil-plant system modeling aims to capture the interactions of the key processes and drivers in the soil-plant-climate continuum to quantify how they determine productivity and environmental outcomes. Modeling has been widely used to evaluate management options for increasing crop yields<sup>[9]</sup>, maintaining soil fertility<sup>[15,16]</sup> and reducing greenhouse gas emissions<sup>[10]</sup>. It enables quantification of the economic and environmental values of soil properties for a given climate and management, thus helping to quantify some key aspects of soil quality.

The objective of this paper is to demonstrate the idea of using soil-plant systems modeling to improve soil management and soil quality. We start with the key soil functional properties and how they interact with climate to determine crop yield potential and environmental impacts in a crop production system. We then illustrate how process-based soil-plant modeling helps in the design of practices that enhance crop productivity while reducing environmental footprints on a given soil or a range of soils. Finally, we discuss and propose future steps in terms of improving soil management and soil quality.

## 2 Soil functional properties and their impacts

Soil properties can be categorized as physical, chemical and biological, with each category having a long list of properties. Here we do not intend to give a comprehensive list of soil properties but rather concentrate on a discussion of how several of the key soil properties function through interaction with climate and management to determine a productivity or environmental outcome. [Table 1](#) lists some

key soil functional properties and their essential roles in extensive crop production.

We use the term *functional property* to emphasize the function or impact of a soil property in the crop production process. This also implies soil properties in a surrogate form and ignores any details that are least relevant to our goals. For example, available water capacity (AWC) depends on soil texture and soil depth, with soil texture determining the hydraulic properties of water content at saturation (SAT), drained upper limit (DUL) and lower limit of crop water use at 1500 kPa suction (LL15). Water availability to crops is not directly related to SAT, DUL or LL15, but to the capacity of the soil to hold water. The term AWC refers to the amount of water held between DUL and LL15 across the root zone. AWC is therefore selected as a functional soil property instead of DUL and LL15. The same applies to infiltration rate and conductivity.

Although all the soil properties listed in [Table 1](#) can be measured directly through soil sampling and other methods, their impacts on crop productivity and environments cannot be quantified without placing them in a climate-management context. For example, a soil with a large AWC is always beneficial because it holds more water for crops to use. However, the impact of a given AWC on crop productivity or nitrogen (N) leaching will always be dependent on the type of climate, rainfall patterns, antecedent water content and crops or cropping systems. At a given level of soil organic matter (SOM) content, nutrient delivery from mineralization in soil depends on the rate of SOM decomposition by microbes, and this is also driven by climate and management practices (that affect soil temperature and water conditions). In addition, any impact of mineralization may be offset by fertilizer application that directly add available nutrients to the soil.

This notion of systems thinking for soil quality does not contradict established soil science. Rather, it adds extra value to a given soil property so that it can be better quantified in terms of its impact on productivity and environmental footprints. A well-structured soil with high

**Table 1** Key soil functional properties in crop production systems and their key functions

| Soil functional properties                   | Key functions   |
|--|---|
| Available water capacity                     | Water available to crops, water and nutrient holding in soil    |
| Infiltration rate                            | Runoff and water infiltration to soil                           |
| Water conductivity                           | Water and nutrient (N) movement, drainage and leaching          |
| Soil organic matter                          | Nutrient delivery in soil from mineralization                   |
| Salinity (electrical conductivity)           | Water and nutrient availability for root uptake                 |
| Soil pH                                      | Root growth, toxicity, water and nutrient uptake                |
| <i>Available water content</i>               | <i>Water uptake</i>   |
| <i>Available macronutrients (N, P and K)</i> | <i>Nutrient uptake, crop growth and environmental footprint</i> |
| <i>Available micronutrients</i>              | <i>Nutrient uptake, crop growth</i>                             |

Note: Properties in italics are more dynamic and subject to much faster change with management.

organic matter content is fertile in most climates. However, to what extent it can support crop productivity and ecosystems services is dependent on climate and how the systems are managed. This view also helps to focus on soil functions rather than individual properties. The properties listed in Table 1 do not distinguish soil types and soil classes, though the latter can help to determine these functional properties.

### 3 Agricultural systems modeling

Process-based soil-plant modeling forms a key part of the modeling of agricultural production systems. Among many other such models, the Agricultural Production Systems Simulator (APSIM)<sup>[17]</sup> has been widely used in both Australia and China to assist in research question formulation, design of crops and cropping systems, and improvement in management practices to achieve enhanced productivity and sustainability of agricultural systems.

APSIM simulates key soil and plant processes and how they respond to drivers (solar radiation, temperature, soil water and nutrient contents) and interact to influence crop growth, yield and environmental outcomes. Soil processes include those controlling field water balance (runoff, infiltration, evaporation, crop uptake, saturated and unsaturated flow in soil, and drainage beyond the root zone), soil and surface organic matter decomposition, and N transformations (mineralization, immobilization, nitrification, denitrification, volatilization), N translocation and leaching. APSIM simulates the phenological development, canopy development, resource capture (light, water and nutrients), biomass growth and partitioning, yield formation and nutrient removal of various crops, either a single crop or crop rotations or intercropping. In addition, APSIM can simulate crop response to phosphorus (P) addition. This allows flexible specification of management scenarios including rotation systems, residue management, tillage, irrigation and fertilization.

A model is a simplified representation of a real system,

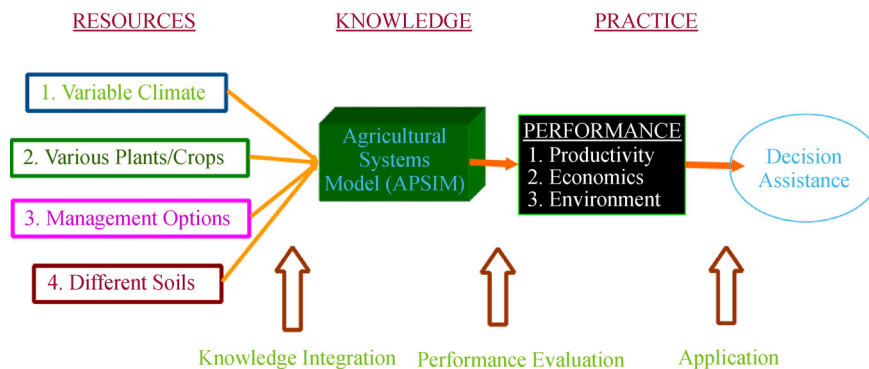
thus uncertainties in model simulations are unavoidable, but these can be minimized. Model validation against a wide range of experimental data are needed in order for a model to generate reliable simulations. Extensive validation of APSIM in both Australia and China has demonstrated its ability to reliably simulate crop and soil processes and their impacts on the performance of cropping systems<sup>[9,18–24]</sup>.

Once confidence in modeling is achieved it is a powerful tool to do scenario modeling and explore the performance of any soil-crop-climate-management systems (Fig. 1). Performance can include productivity, economic return (gross margin) and impacts on the environment. In such a framework, APSIM is a valuable tool for integrating knowledge and data, and using them to evaluate possible combinations of resources (climate, soil, crops and management options) in terms of system performance to assist in decision-making and enhance productivity and sustainability.

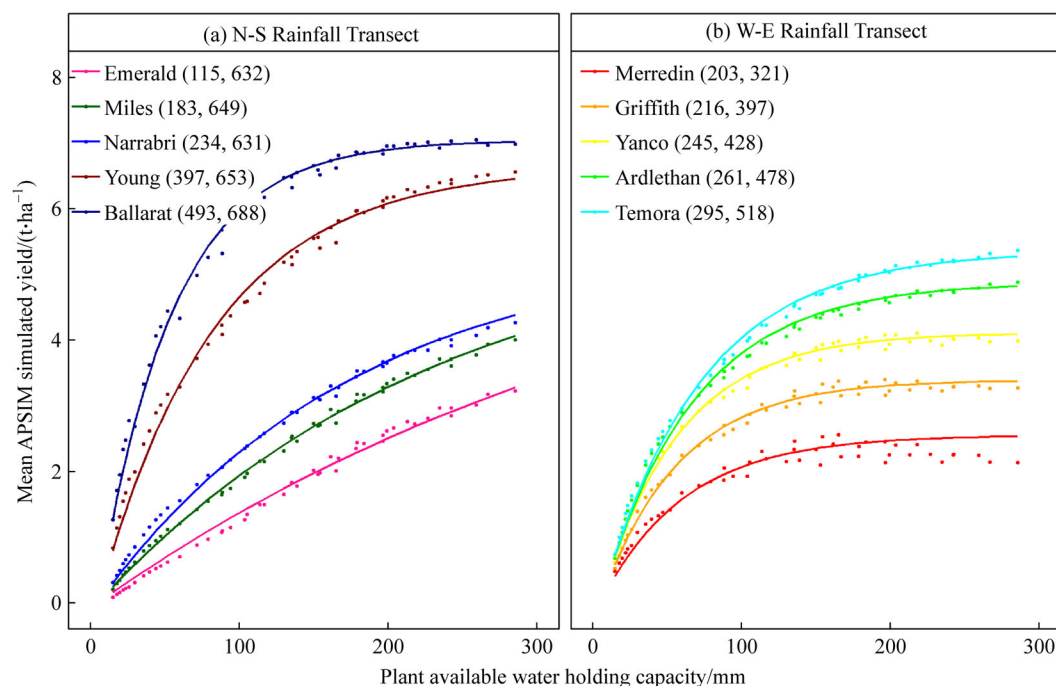
### 4 Managing soils versus managing the system

Figure 1 highlights the key contribution of soil as part of agricultural systems. However, it is not the only component that needs to be managed. To realize the potential of soil to support/sustain crop production and maintain or enhance environmental quality, matching crops and cropping systems to the climate becomes a key component of systems management. Any soil management needs to be aligned with crop management to achieve the expected productivity and environmental targets.

Here, we give three examples to illustrate how we have used the systems modeling approach to quantify the impact of soil functional properties and to improve management. The first example illustrates the impact of plant available water capacity (PAWC) of soil on dryland wheat yield potential across contrasting climatic regions of Australia<sup>[7]</sup> (Fig. 2). The results show the long-term average of



**Fig. 1** Agricultural system simulation model APSIM as a tool to integrate knowledge and data for evaluating the performance of crop-soil-climate-management systems to assist in management decision-making.



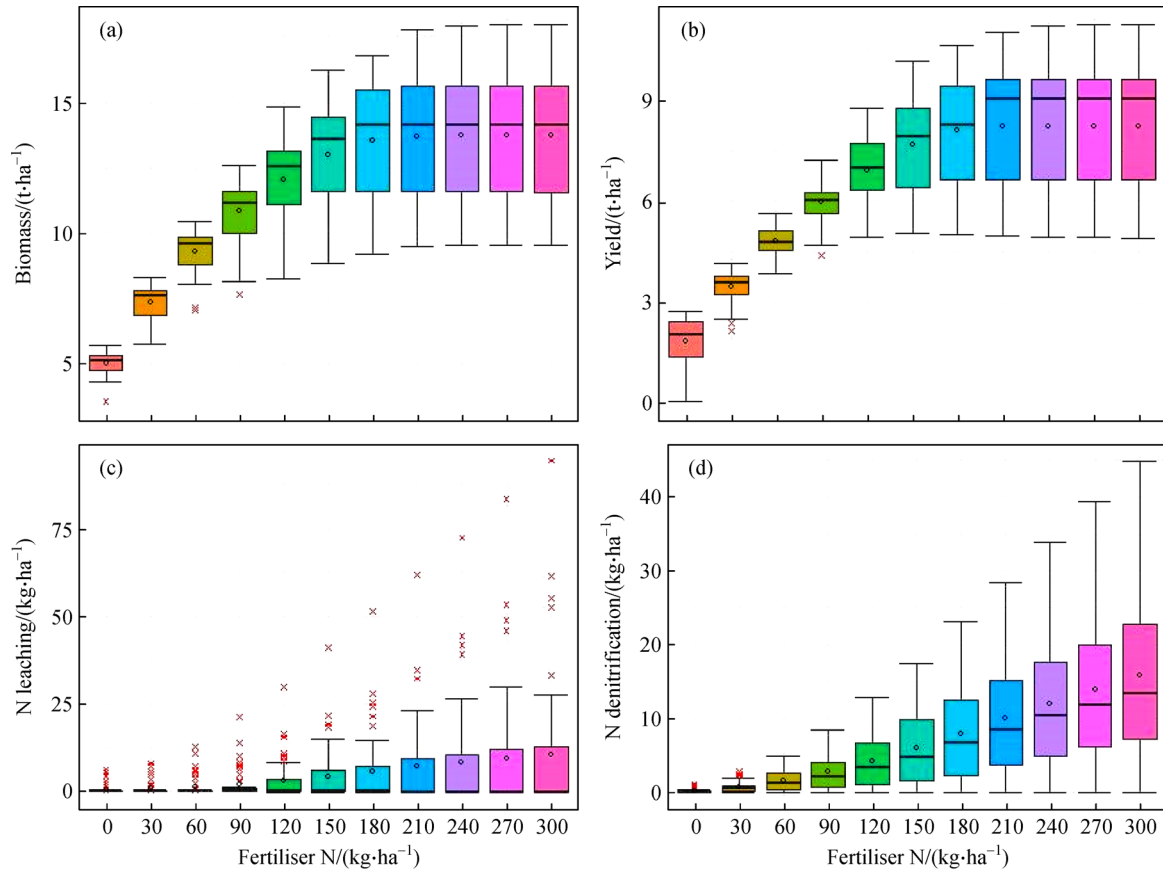
**Fig. 2** Impact of plant available water holding capacity (PAWC) of soil on the average APSIM simulated 120-year wheat yield potential under rainfed conditions across contrasting climatic regions of Australia. (a) Sites along the north-south (N-S) rainfall transect roughly following the 650 mm annual rainfall isohyet where rainfall pattern changes from summer dominant to winter dominant rainfall; (b) sites along the west-east (W-E) rainfall transect with similar rainfall pattern where annual rainfall increases from west to east. The first number in the legend shows the 120-year average in-crop season (May–October) rainfall (mm) and the second number is the average annual rainfall (mm) at each site. Adapted from He and Wang et al.<sup>[7]</sup>, with permission from Elsevier.

simulated wheat yield potential under dryland conditions (no irrigation) in response to a wide range of PAWC, which would be difficult to generate using an experimental approach. While a larger PAWC is always beneficial across all sites, a PAWC > 200 mm enables wheat yields of > 6 t·ha<sup>-1</sup> to be achieved at wet sites (Young and Ballarat). Soil with such a large PAWC would have little value compared to a soil with a PAWC of 150 mm at drier sites (Merredin and Griffith) because crop growth at the drier sites is limited by the available rainfall rather than by the capacity of the soil to store the water.

The second example demonstrates how N management of a given soil and climate combination leads to different productivity and environmental outcomes. Figure 3 shows the results of simulated biomass and yield of maize on a soil with a PAWC of 254 mm together with the N losses through denitrification and leaching at Wuqiao on the North China Plain<sup>[9]</sup>. Both crop productivity (biomass and yield) and N losses (denitrification and leaching) increase with N application rate, but the magnitude of increase at different N rates are markedly different (Fig. 3). A N rate of 150–180 kg·ha<sup>-1</sup> N would lead to near-maximum productivity in biomass (Fig. 3(a)) and yield (Fig. 3(b)), but with small N losses (Fig. 3(c,d)), particularly when calculated as N loss per kg grain produced. Higher N rates result in little additional gain in production, but a

significant increase in N loss. Lower N rates would have minimum impact on N loss, but a sharp decline in productivity. However, when the crop was changed from maize to a summer legume crop such as soybean, these response curves were distinctly different due to the lower productivity of soybean, biological N<sub>2</sub> fixation capacity and consequently much lower or no fertilizer N requirement. This clearly demonstrates that soil management must be in the context of soil-plant-climate systems, with well-defined targets.

The third example shows how systems modeling helps to develop a plan for managing the mineral N bank in soil to achieve productivity, economic and environmental outcomes<sup>[25]</sup>. With dryland farming under a highly variable climate in Australia, crop N demand is dependent on yield potential that is unknown at the time of fertilizer decision making due to uncertain rainfall in the coming season. This makes N decisions extremely difficult and risky. Our modeling results show that such decisions can be made easier by maintaining a certain level of mineral N in the topsoil at the crop tillering stage through N fertilizer application. At the study site Young, maintaining a mineral N level of 150 kg·ha<sup>-1</sup> N enables the wheat crop to achieve a high yield potential up to 7 t·ha<sup>-1</sup> (Fig. 4(a)), with no significant increase in N leaching, even in wet years (Fig. 4(b)) and a highly acceptable 6-fold return on



**Fig. 3** Simulated ranges of (a) aboveground biomass, (b) grain yield, (c) N loss from leaching, and (d) N loss from denitrification in response to fertilizer N input rates to continuous maize at Wuqiao (1970–2012). The box boundaries indicate the 25th and 75th percentiles and the solid lines indicate the median, and the whiskers extend to the 5th and 95th percentiles, with the average shown by a black circle. The red crosses are the outliers. Adapted from Zhao et al.<sup>[9]</sup>, with permission from Elsevier.

investment (Fig. 4(c)). In addition, this management will result in an increase in soil carbon content and soil fertility, i.e., soil quality (Fig. 4(d)).

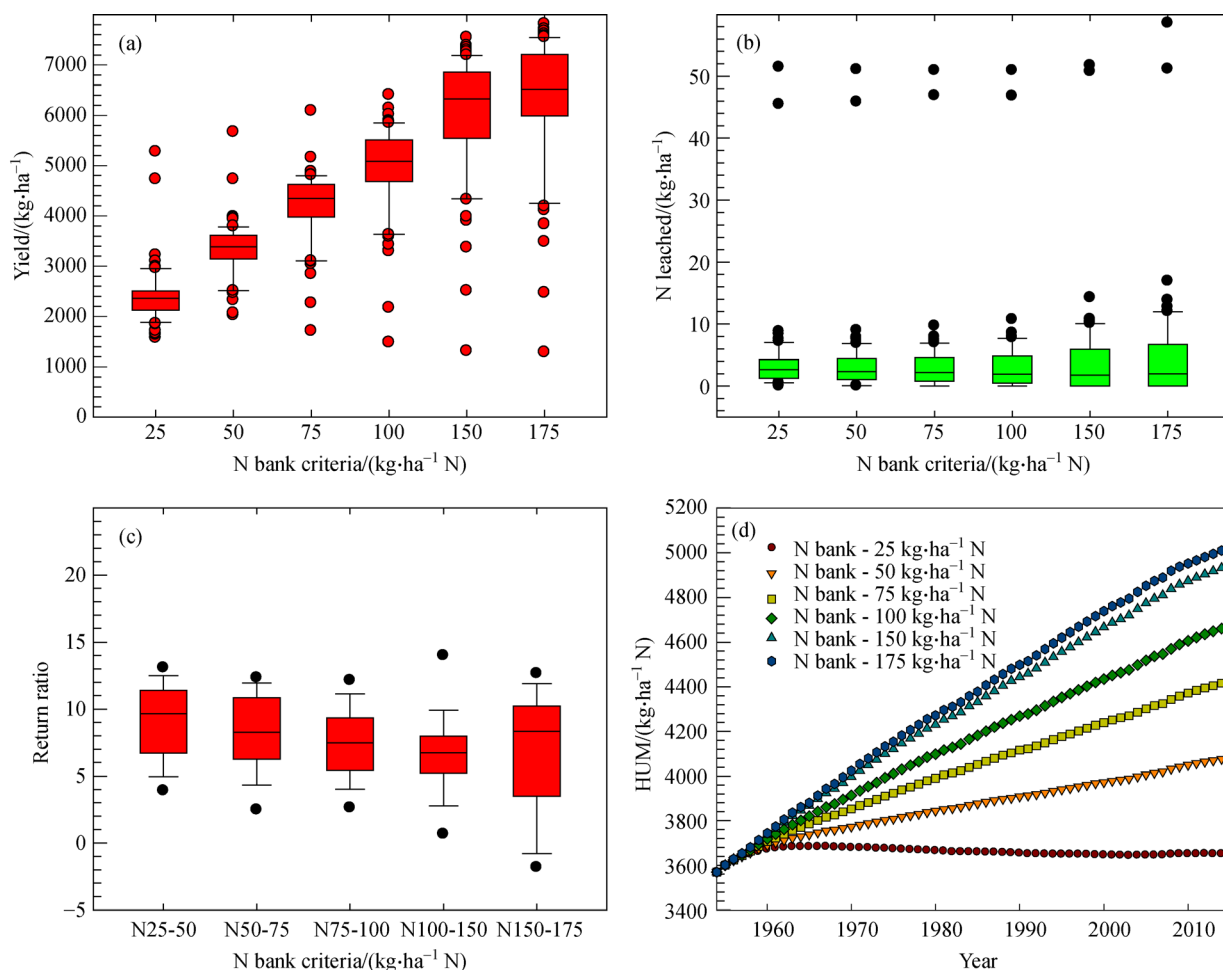
These examples demonstrate that a systems modeling approach can be used in the development of strategies for improved productivity, economic return and environmental outcomes of agricultural ecosystems. Soil management in such a framework is an integral part of system management and must not be ignored. In this systems context, soil quality and soil health are not defined narrowly using soil properties alone, rather they need to be quantified in terms of productivity and economic and environmental performance of the crop production system that the soil sustains. In this regard, a soil has its economic and environmental values depending on the prevailing climatic conditions and how it is managed for the purpose of crop production and/or ecosystem services. The impact of a variable climate can be assessed using average crop productivity (Fig. 2) or variability in crop productivity or environmental footprint (Fig. 3, Fig. 4).

Our discussions so far have focused on soil management in agricultural production systems. The concept would also

apply to other ecosystems but with quite different management targets. For example, an acid coastal sandy heathland can support very high biodiversity but is not productive in an agricultural sense. In that case, soil health and soil quality need to be quantified with their ecological service values rather than agricultural productivity.

## 5 Conclusions

We argue that the difficulties in establishing a consensus on the key indicators to define and quantify soil quality and soil health are due to the established focus on soil properties alone. If we consider soil quality as the capacity of soil to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health<sup>[2]</sup>, it must be quantified in terms of crop productivity and impact on ecosystems services that are also strongly driven by climate and management interventions. A systems modeling approach captures the interactions of climate, soil, crops and management, and their impact on system performance, thus helps to quantify the



**Fig. 4** The effect of maintaining a N bank of mineral N ( $\text{kg}\cdot\text{ha}^{-1}$  N) in the surface 0.4 cm of the soil profile at mid-July (near crop tillering) on (a) yield, (b) N leached, (c) return ratio to the N applied to satisfy the N bank criteria, and (d) the changes in the humus pool of a Red Chromosol at Young, NSW, Australia. Horizontal bars and upper and lower edges of boxes indicate 10th, 25th, 75th and 90th percentiles, median (solid lines) and mean (dotted line) in the box. The solid circles represent the 5th and 95th percentiles. Adapted from Smith et al.<sup>[25]</sup>, with permission from Elsevier.

value of soil in terms of crop productivity, economic return and environmental footprints. In such a systems context, soil management must be an integral part of systems management that also include managing the crops and cropping systems under specific climatic conditions, with a view of future climate change.

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