Modelling of the degree of organic carbon sequestration (SOC) in soils

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Outlines

- Introduction
- SOC change over time
- Variability in data
- Model features
- Why use models
- Rothemsted Model (RothC- model)
- A case study- by Century model
- Conclusions

SOC change over time

- The most direct means of determining soil carbon **se**questration is to measure, over time, **se**quential changes in soil carbon.

- Such measurements **are** complicated by **the** spatial and temporal heterogeneity of soil carbon contents and its slow relative rate change.

- Soil carbon **can** exhibit significant field-scale variability due to spatially varying topography and parent material or past differences in vegetation or management history.

SOC change over time

- Climate change and increasing area of degraded soils require stable indicators and models for soil organic carbon sequestration (Grunwald, 2010).

- Soil carbon changes in response **to changes** in management practices(e.g., tillage, crop type and rotation, fertilization etc.) have been modeled extensively.

- The most widely used simulation models conceptualize SOM as being composed of **3** to ***4*** fractions, which vary in physical and chemical properties affecting turnover rates**.**

Variability in data

- Although we can measure SOC with some degree of accuracy and defined uncertainty, the amount of plant root material is scarcely measured, instead estimating it from above ground production using an assumed root-shoot ratio [Liu et al. [2009].

- A well tested simulation model is clearly an efficient means of addressing many aspects beyond the possibility of experimental measurement and provides proof of concept for long-term management systems without being conflicted by cost and experimental error associated with repeated measures.

Variability in data

- One of the problems in measured SOC data reported is its large variation that is attributed to many reasons including the lack of resource for conducting far more than the actual subsamples taken.

- An example of this problem is taken from a well managed long term experiment (Figure on next slide).

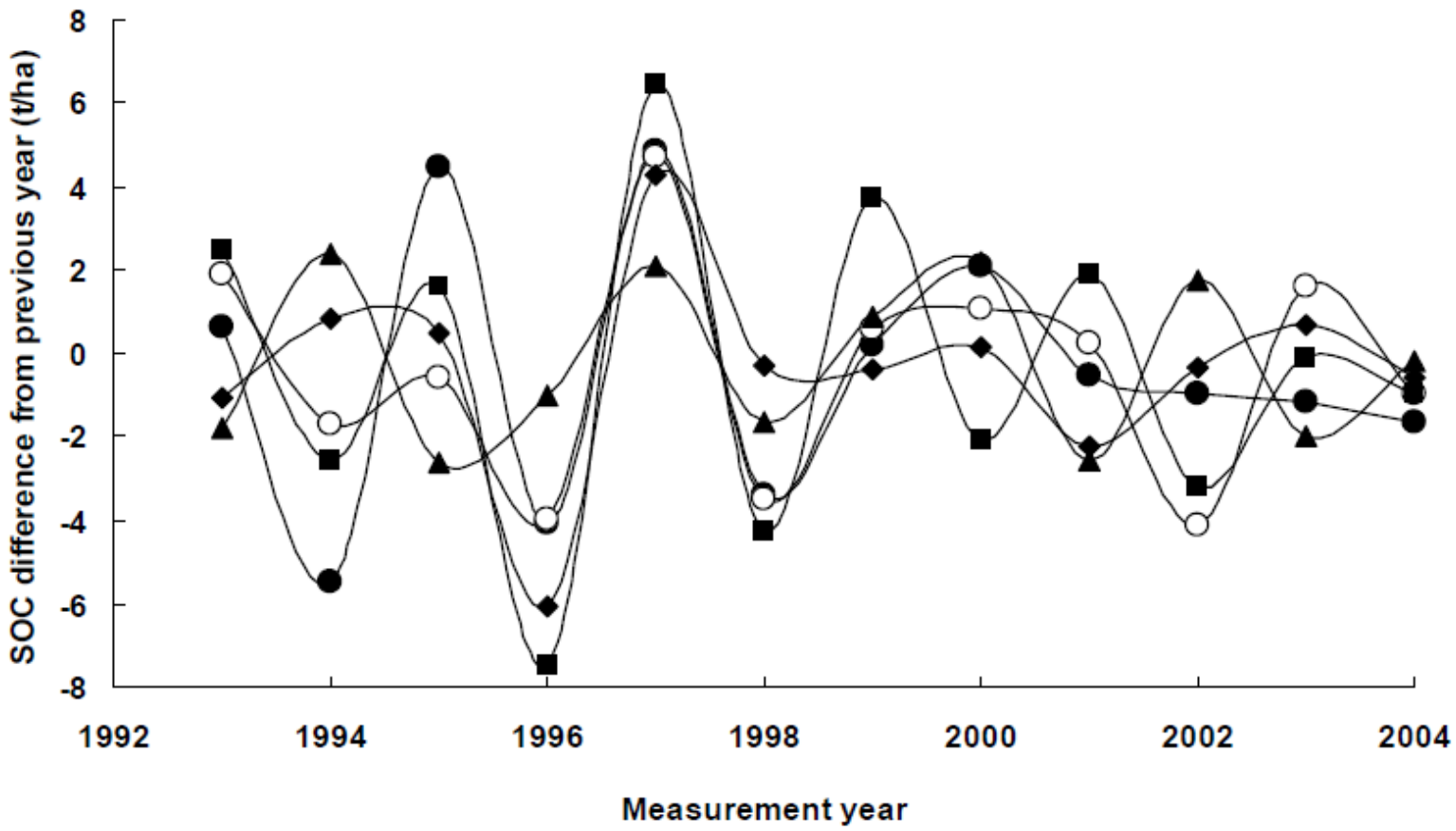


Figure 1: The difference in soil organic carbon (SOC) measured between two consecutive years from a long term cropping experiment (data reanalysed from Liu et al. [2009]). No-tillage - stubble retained WL (●), Conventional cultivation - Stubble retained WL (○), No-tillage - Stubble burnt WL (▲), Conventional cultivation - Stubble burnt WL (■), Conventional cultivation - Stubble burnt WW (◆), WL: Wheat-lupin rotation, WW: Wheat-wheat rotation O'Leary et al. (2015)

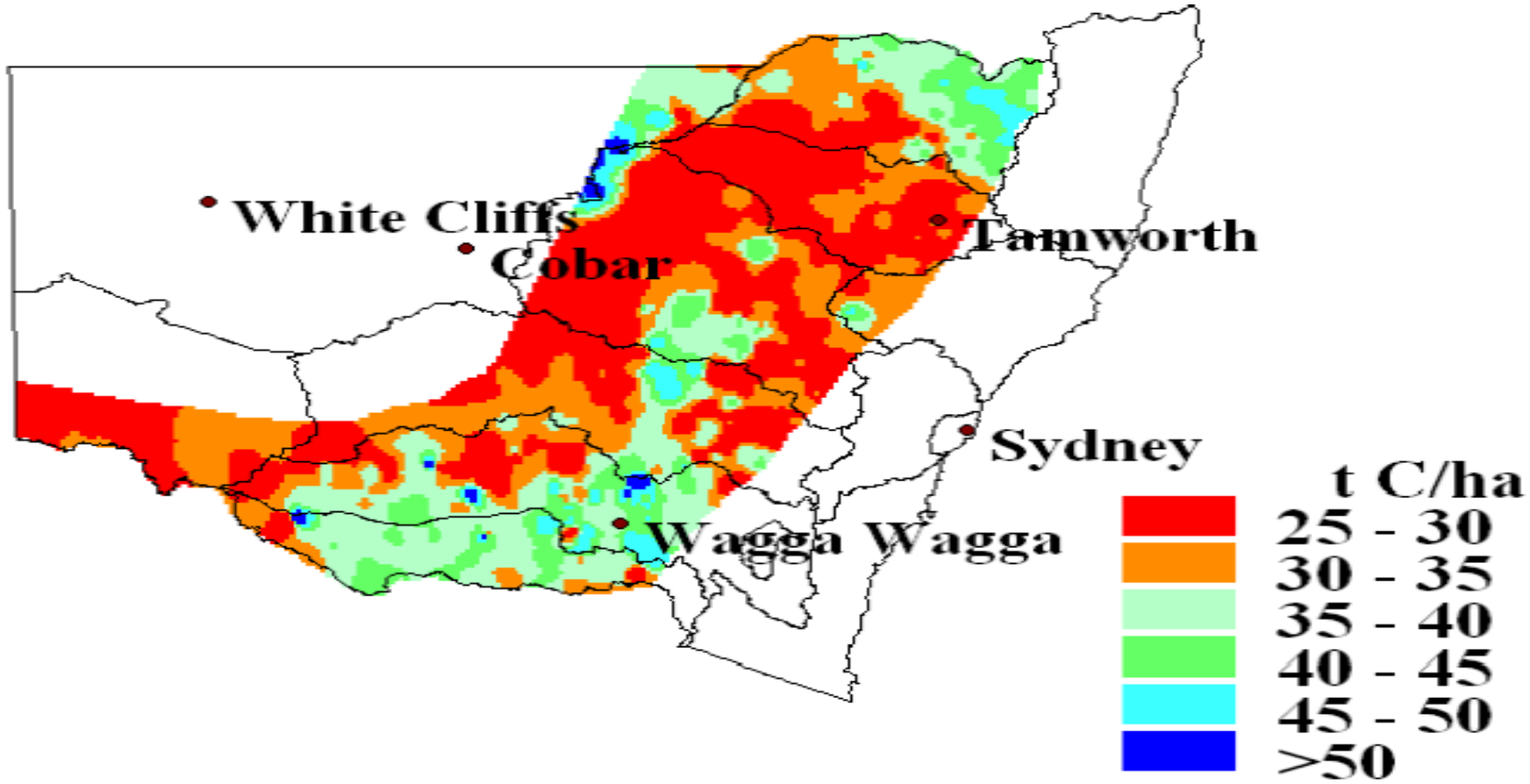


Figure 2: Simulated soil organic carbon (SOC 0-30 cm) equilibration level over New South Wales showing the large spatial variation in SOC from 25 to over 50 t/ha after 50 years under a present climate cropping regime with 26% residue incorporation (from Liu et al. [2014). O'Leary et al. (2015)

Model features

- Some models simulate crop growth and residue inputs directly, while others require that organic matter addition rates be specified as inputs to the model.

- The environmental factors controlling **SOM** in most models include soil temperature and moisture, soil aeration or drainage class, soil texture, **and** mineralogy.

-

Model features

- The rate of organic matter input **as** crop residues, manure, sludge, or other amendments is a major determinant of soil carbon levels.

- The measurement of components of the soil involved in SOC dynamics is fundamental to any carbon modelling effort.

- Standards need to be set so that others can repeat the observations.

Model features

- Most soil carbon models are based on first-order decay of soil organic carbon with the role of microbes as decomposers controlling the decay rates [Allison et al. 2010].

- Consequently, SOC is the result of the equilibrium balance of carbon inputs from plant-derived materials and outputs through decomposition affected by soil water and clay content and temperature.

- Modelling employing mechanistic and explanatory variables offers a way to break free of this limitation, particularly with their ability to easily examine practices that have not been experimentally tested.

Model features

- Thus, soil organic carbon modeling is one of the most essential tools for determining the effects of organic material management on carbon sequestration (Xu et al., 2013)

- Long-term field are aimed to monitor soil organic carbon (SOC) dynamics as affected by management practices.

- However, large dependency of SOC dynamic on soil and climatic conditions may create uncertainity in monitoring dynamics of SOC for post-future influence of soil management practices (Xu et al., 2013).

Model features

- Mathematical modeling of soil carbon dynamics is relatively well developed, particularly for agricultural soils.

- Models have been used to investigate how SOM varies across regions and landscapes **as** a function of climate, vegetation, topography, soils, and other environmental factors.

Why modelling?

- The main advantages of SOC modeling are:
  - -explanation of processes and relationships in soil-plant-atmosphere system
  - - improvement in the clarity of SOC dynamics.
- Therefore, SOC modeling is useful to study the effects of various management scenarios on carbon sequestration and hence, mitigation of climate change (Fry et al., 2013).

Why modelling?

- Many soil carbon models have been quite **successful** in simulating carbon dynamics at the field scale, but they generally require some degree of site-specific calibration.

- Many models are available for the estimation of organic carbon stock, and among them the most widely used are:

- RothC and CENTURY models with a high potential in application to predict SOC stock on regional as well as national level (Barancikova et al., 2010; Smith et al., 2007) ; Shrestha et al. 2009)

Table 3
Methods used in carbon sequestration assessment studies for land use change (LUC) and management change based on observations and models.

LCA method used	Key features	Time horizon	Agricultural system and crop	Crop management	Carbon storage (t C ha^{-1} yr^{-1})	References
IPCC Tier I	Employ constant default factor for soil carbon change derived from an international body of studies	20	Annual crops	CT to NT Decrease fallow Increase perennials	0.23 ± 0.66 1.05 ± 0.72 1.87 ± 0.46	VandenBygaart et al., 2008
ICBM	Estimate long-term trends in SOC dynamics based on soil climate and management parameters	41	Wheat	–	2.3	Congreves et al., 2015
Roth C	Estimate turnover of organic carbon in aerobic soil based on soil type, temp, moisture and crop	24	Maize- wheat	Traditional tillage to conservation tillage	3.3 & 2.1 (measured and modeled)	Molina et al., 2017
C- Tool	Simulates soil C dynamics on the basis of soil characteristics, C inputs, and climate	20 100 200	Soybean	Conventional to organic	0.143 0.60 0.32	Petersen et al., 2013
CENTURY	Simulate long-term dynamics of carbon based on climatic parameters, SOM fractions and soil texture	30	Corn	Various tillage and residue management	−0.35–0.54 Phosphorus alone to phosphorus and nitrogen	Kwon et al., 2013
CropSyst	multi-year and multi-crop simulation model, was used to evaluate emissions and SOC change	30	Wheat	CT to NT	0.15	Zaher et al., 2013
The terrestrial ecosystem model (TEM)	Global scale model estimates carbon (C) fluxes interrestrial ecosystems based on climate and ecological data	50	Corn, soybean, and wheat to Switchgrass and Miscanthus	Tillage and residue removal	0.67–0.95	Qin et al., 2012
Measurement	Site specific assessment	27	Rice-wheat	Different INM	0.23–0.62	Nayak et al., 2012

CT: Conventional tillage; NT: No tillage; INM: Integrated nutrient management; ICBM: Introductory Carbon Balance Model; Roth C: The Rothamsted carbon model; C– Tool: A simple tool for simulation of soil carbon turnover; CENTURY model: Soil Organic Matter Model Environment; CropSyst: Cropping Systems Simulation Model; The TEM: Terrestrial ecosystem model.

Adopted from Nayak et al. (2019)

Roth C model

- The RothC model is a widely used soil organic matter (SOM) decomposition model used to simulate the C dynamics in agricultural soils under various environments and management practices (Smith et al., 2005; Guo et al.,2007).

Roth C model

- The soil carbon pool in the RothC model is divided into five conceptual components, i.e.,

  -decomposable plant material (DPM),

  -resistant plant material (RPM),

  -microbial biomass (BIO),

  -humified organic matter (HUM),

  -inert organic matter (IOM)

Roth C model

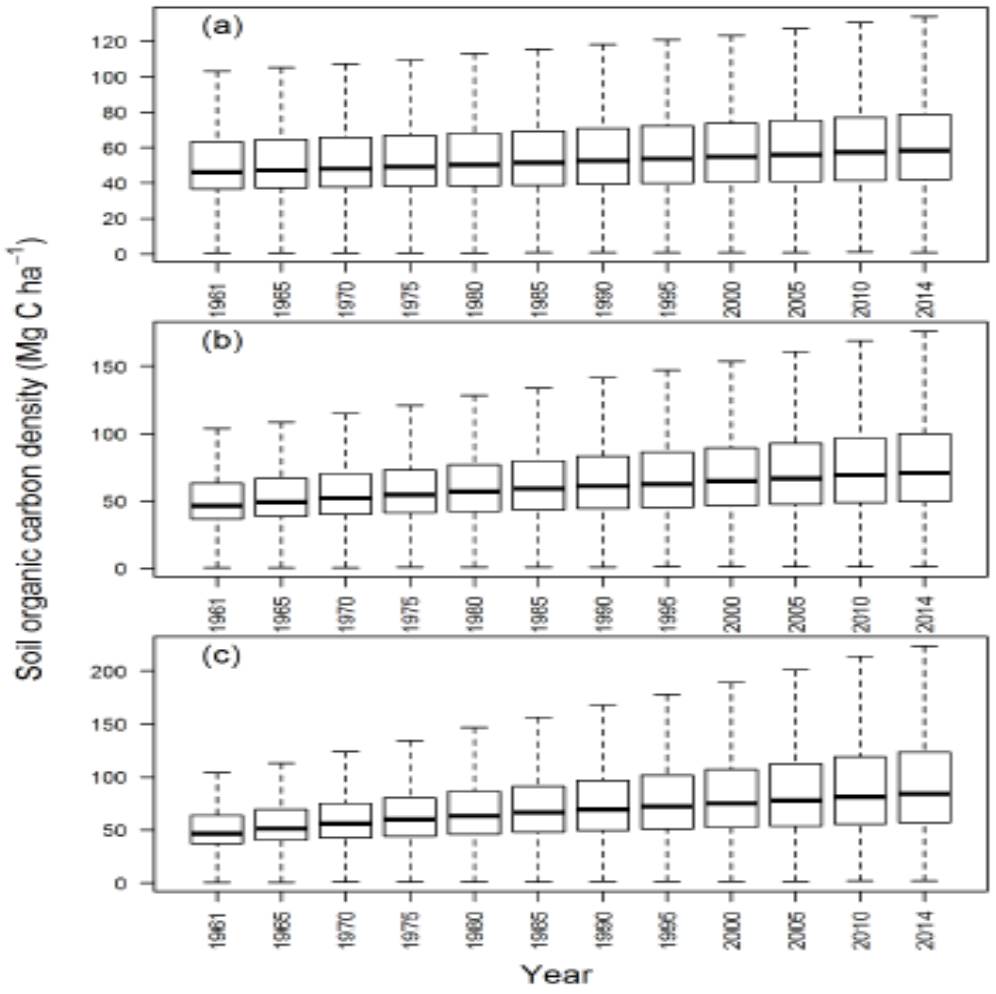
These conceptual pools are difficult to measure directly in most cases and can only be empirically initialized because only the quantity of total soil organic carbon is obtainable without finer level partitioning among the subpools

RothC model

- The main advantages of RothC model is necessity to provide only a basic input data that are readily available such as: monthly rainfall, average monthly air temperature and others (full description is available by Coleman and Jenkinson, 1996)

- RothC model has been widely used in many countries for many years.
- Some examples of Roth C are presented in next slides

RothC for SOC

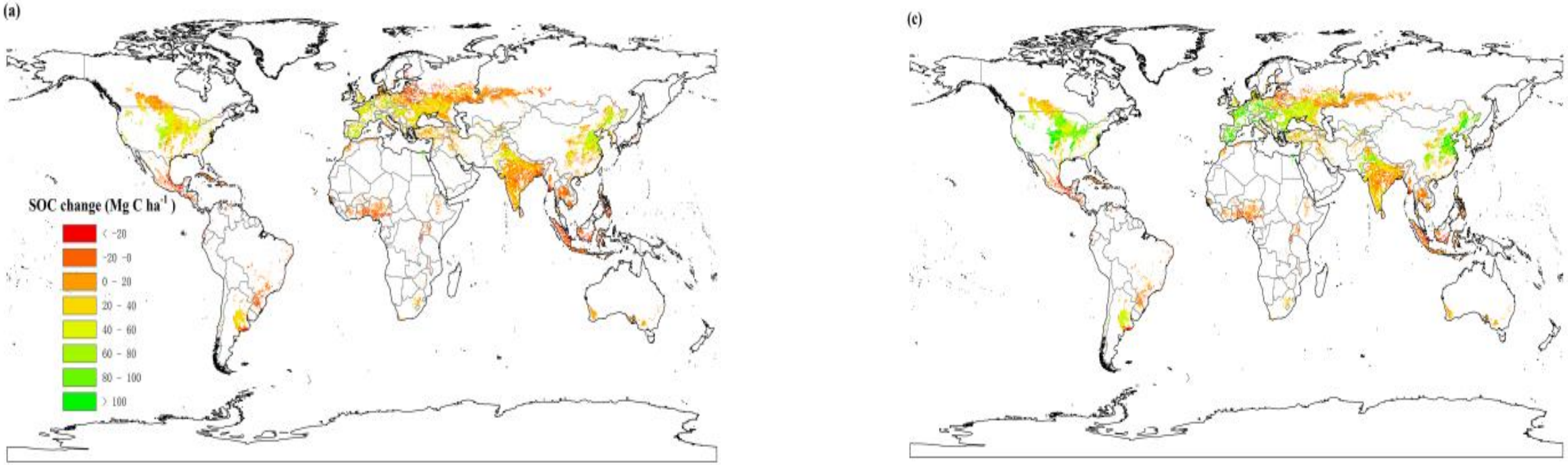


Temporal changes in the soil organic carbon (MgCha-1$_1$) of the main global cereal cropping regions under different aboveground crop residue retention rates of 30% (a), 60% (b) and 90% (c). Box plots show the median and interquartile range with the whiskers extending to the most extreme data points within the 1.5_ (75–25 %) data range (Adopted from Wang et al. 2017)

RothC for SOC

- SOC generally increased over time
- In general, the annual rates of change in SOC were
- 0.22MgCha-1 yr-1 under R30,
- 0.45MgCha-1 yr-1 under R60, and
- 0.69MgCha-1 yr-1 under R90

RothC for SOC



Spatial distribution of the SOC change (1961–2014, MgCha^{-1}) across the main global cereal cropping regions under different above-ground crop residue retention rates of 30% (a) and 90% (c). ((Adopted from Wang et al. 2017)

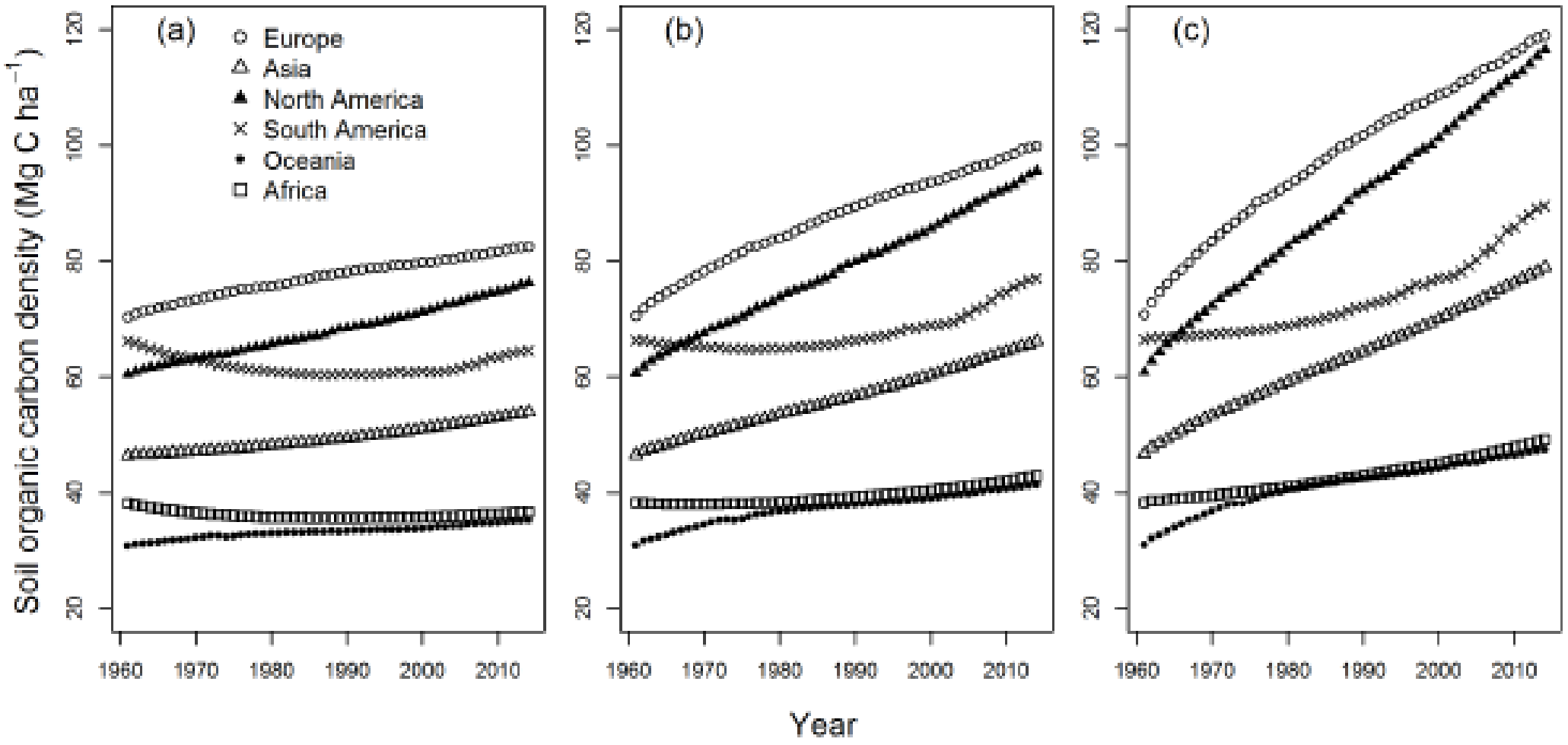
RothC for SOC

- Among the three scenarios, a relatively higher increase in SOC generally occurred in the middle latitudes of the Northern Hemisphere (central parts of the USA, western Europe and the northern regions of China.

- A relatively small increase in SOC generally occurred in the high latitude regions of both the Northern and Southern Hemisphere, while the SOC decreased across the equatorial zones of Asia, Africa and America.

- On a global average, 69 to 89% of the study area acted as a net carbon sink under different residue management scenario.

RothC for SOC



SOC evolution of five continents in the main global cereal cropping regions under different above-ground crop residue retention rates of 30% (a), 60% (b) and 90% (c). (Adopted from Wang et al. 2017)

RothC for SOC

- In general, among the three scenarios, the SOC of the cropland across Europe, Asia and North America showed a linearly increasing trend over time Wang et al. (2017)

- In Oceania, the SOC increased faster in the first two decades and showed a relatively lower increasing rate during the latter three decades .

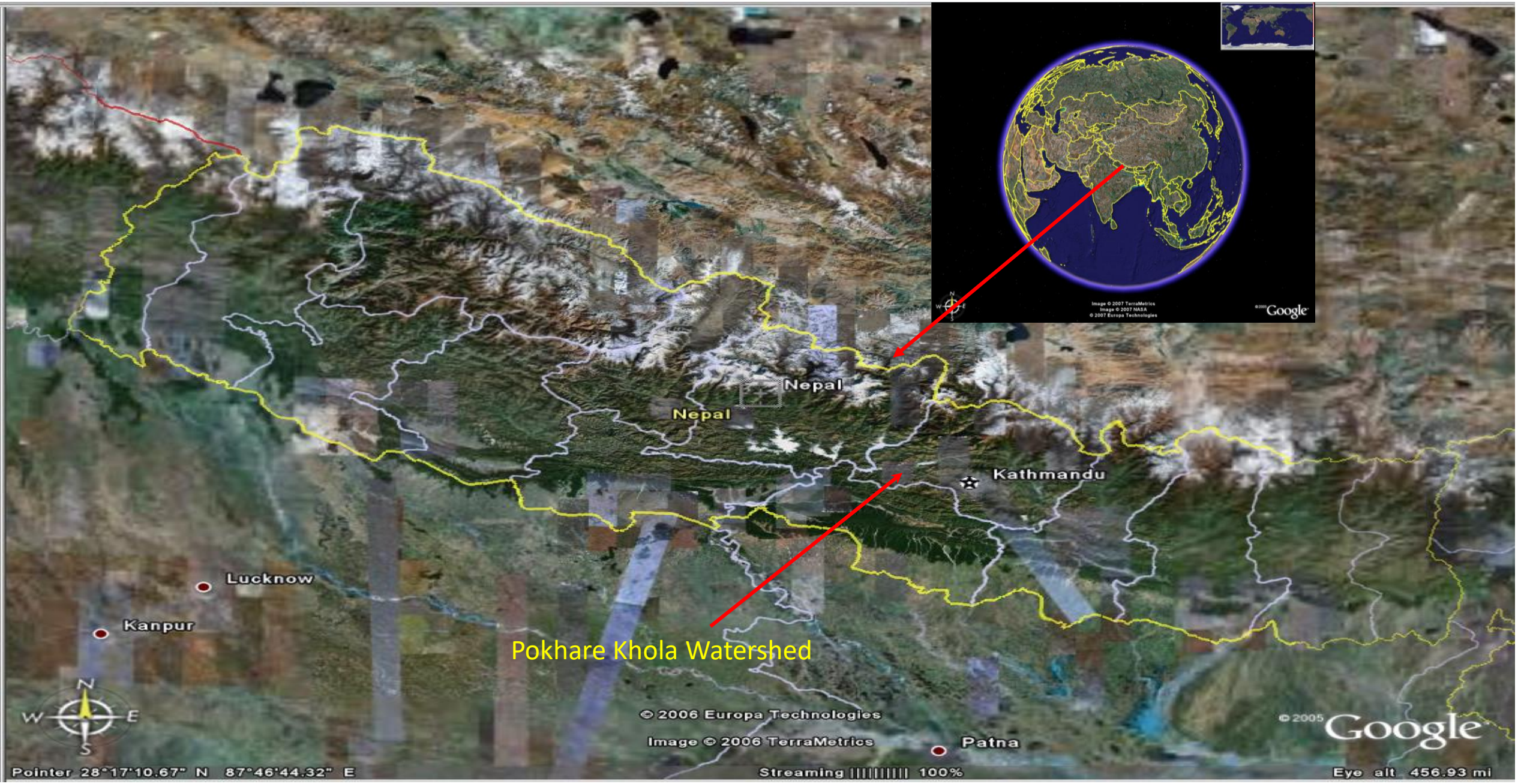
- In South America and Africa, the SOC decreased in the first few decades and increased or remained relatively stable during the latter periods under R30 and R60 .

- Under R90, however, SOC on all continents increased over time.

A case study

Modeling Soil Organic Carbon Stocks and Changes in a Nepalese Watershed

Objective: To assess, analyse and predict the changes in SOC pool, under cultivated and managed forest lands of a mid-hill watershed in Nepal over a period of 100 years (1950-2050) by using the Century model(Shrestha et al. 2009).


Nepal
Nepal
Kathmandu
Lucknow
Kanpur
Pokhare Khola Watershed
Patna
© 2006 Europa Technologies
Image © 2006 TerraMetrics
© 2005 Google
Pointer 28°17'10.67" N 87°46'44.32" E
Streaming 100%
Eye alt 456.93 mi

Pokhare Khola Watershed

Table 1.Major Land uses of Pokhare Khola Watershed

Land use	Cropping pattern / Major Vegetation
Irrigated low land (*Khet*)	Rice-wheat-rice, rice-vegetable-maize, rice-vegetable-vegetable
Rain fed upland (*Bari*)	Maize-millet-vegetable/fallow, maize-vegetable-vegetable, maize-mustard-fallow

Shrestha et al. (2009)

Table 1.Major Land uses of Pokhare Khola Watershed (cont.)

Dense Shorea Forest (DS)	*Shorea robusta, Lagestromia parviflora, Acacia catechu, Dalbergia Sisoo*
Degraded Forest/Shrub land (DF)	*Shorea robusta, Lagestromia parviflora, Acacia catechu, Dalbergia Sisoo*
Pine Shorea Forest (PS)	*Pinus roxburghii, Lagestroemia parviflora, shorea robusta*
Schima Castanopsis Forest (SC)	*Schima walichii, Castanposis indica, Syzygium cumunii*

Shrestha et al. (2009)

CENTURY model

What is CENTURY ?

- **Simple Ecosystem Model**
- **Soil Organic Matter**
- **Plant Production**
- **Hydrological**
- **Nutrient Cycle**

MODEL STRUCTURE

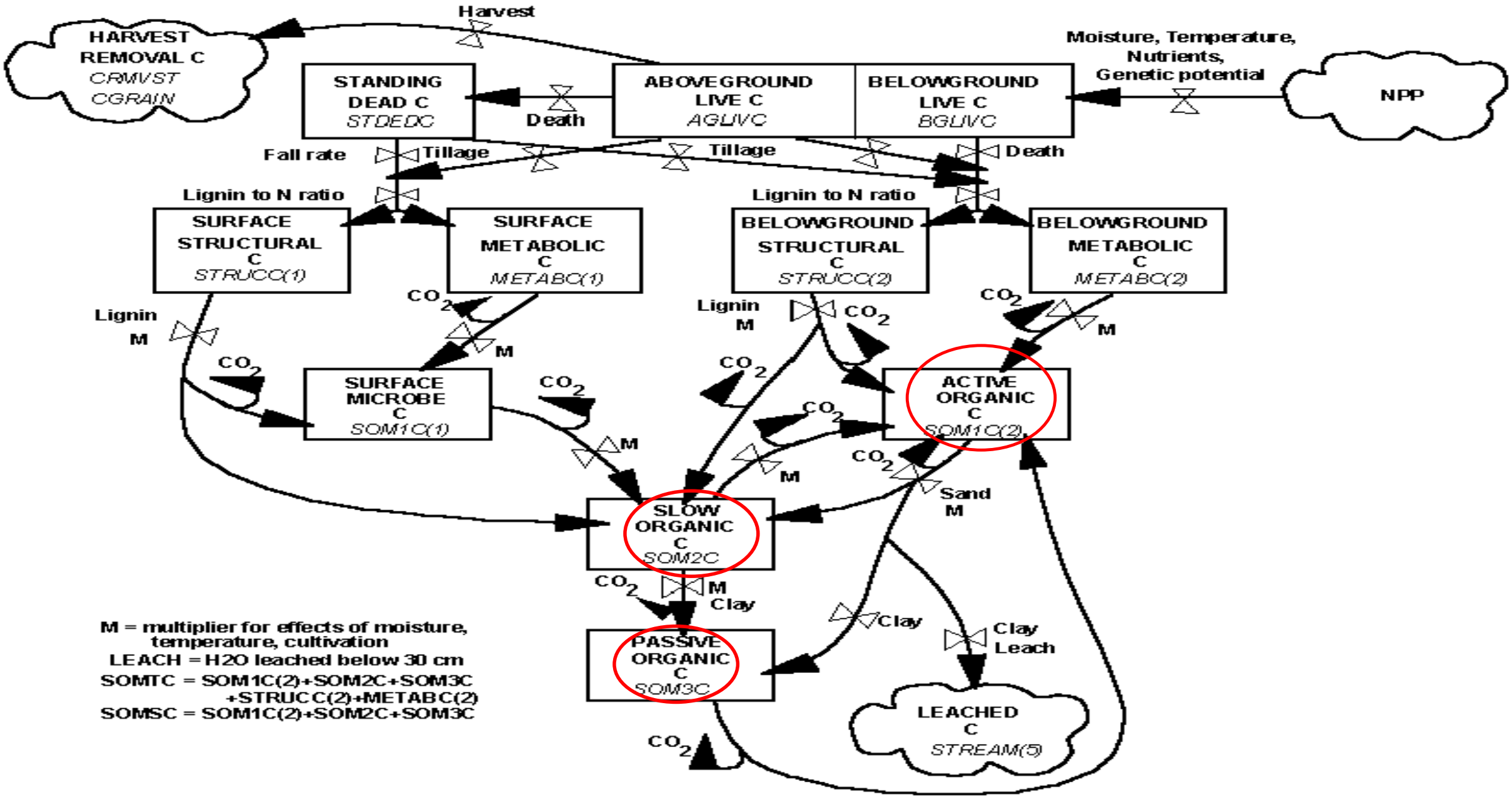
- **Structure based on turnover rates of SOM pools**

- **THREE TYPES OF SOM POOLS**

- **ACTIVE: Live microbes and their by- products**
- **(2 to 5 year turnover)**

- **SLOW: Physically and chemically protected**
- **(20 to 50 years turnovers)**

- **PASSIVE: Physically protected or chemically resistant SOM**
- **(800 to 1200 year turnover)**



Flow diagram for the soil carbon submodel

Effect of land use and land use changes

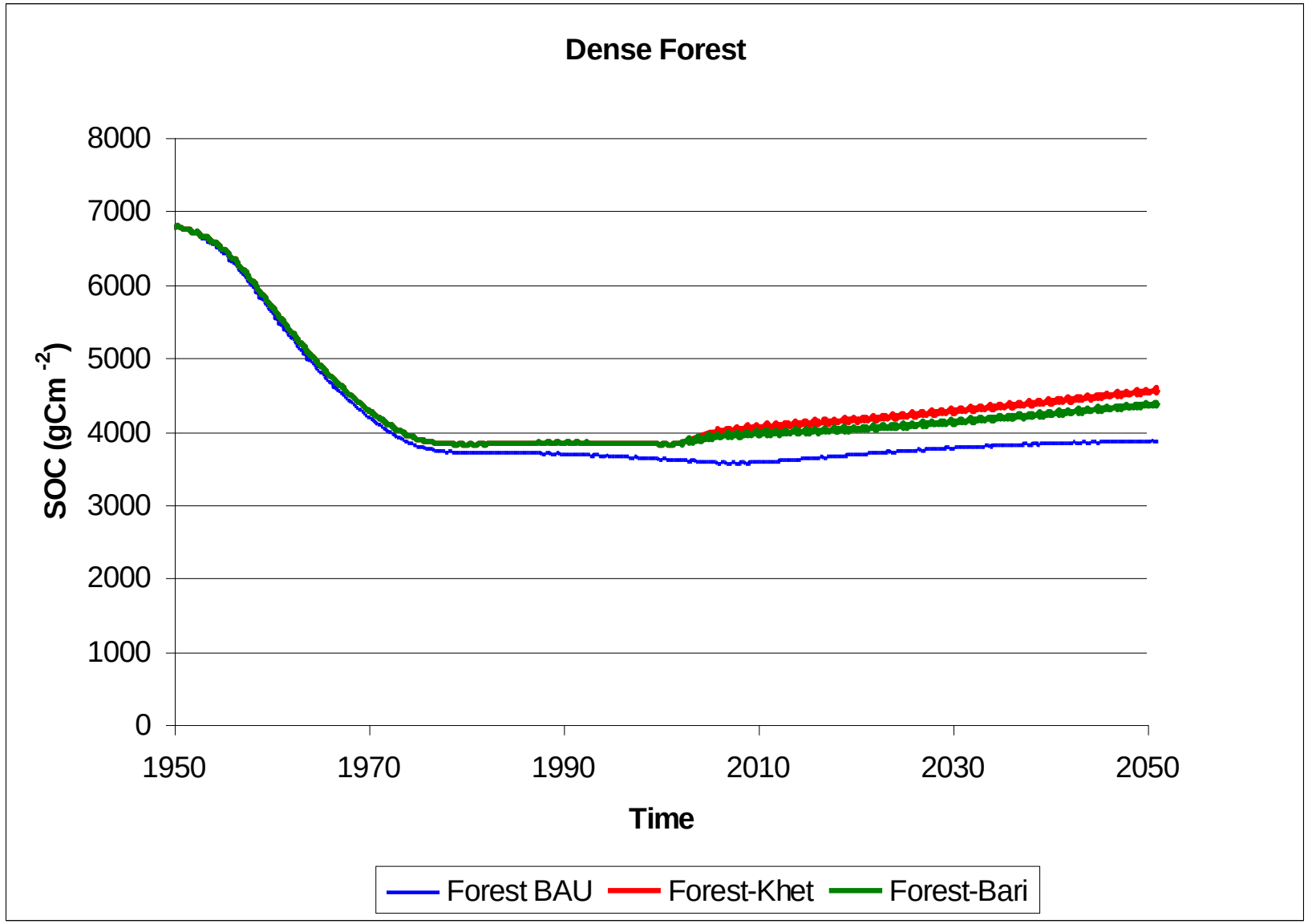


Figure 1: Modelled soil organic carbon (SOC) in Pokhare Khola watershed, Nepal, under different land conversion scenarios: forest remaining forest (BAU), forest to lowland Khet cropping, and forest to upland Bari cropping.

Shrestha et al. (2009)

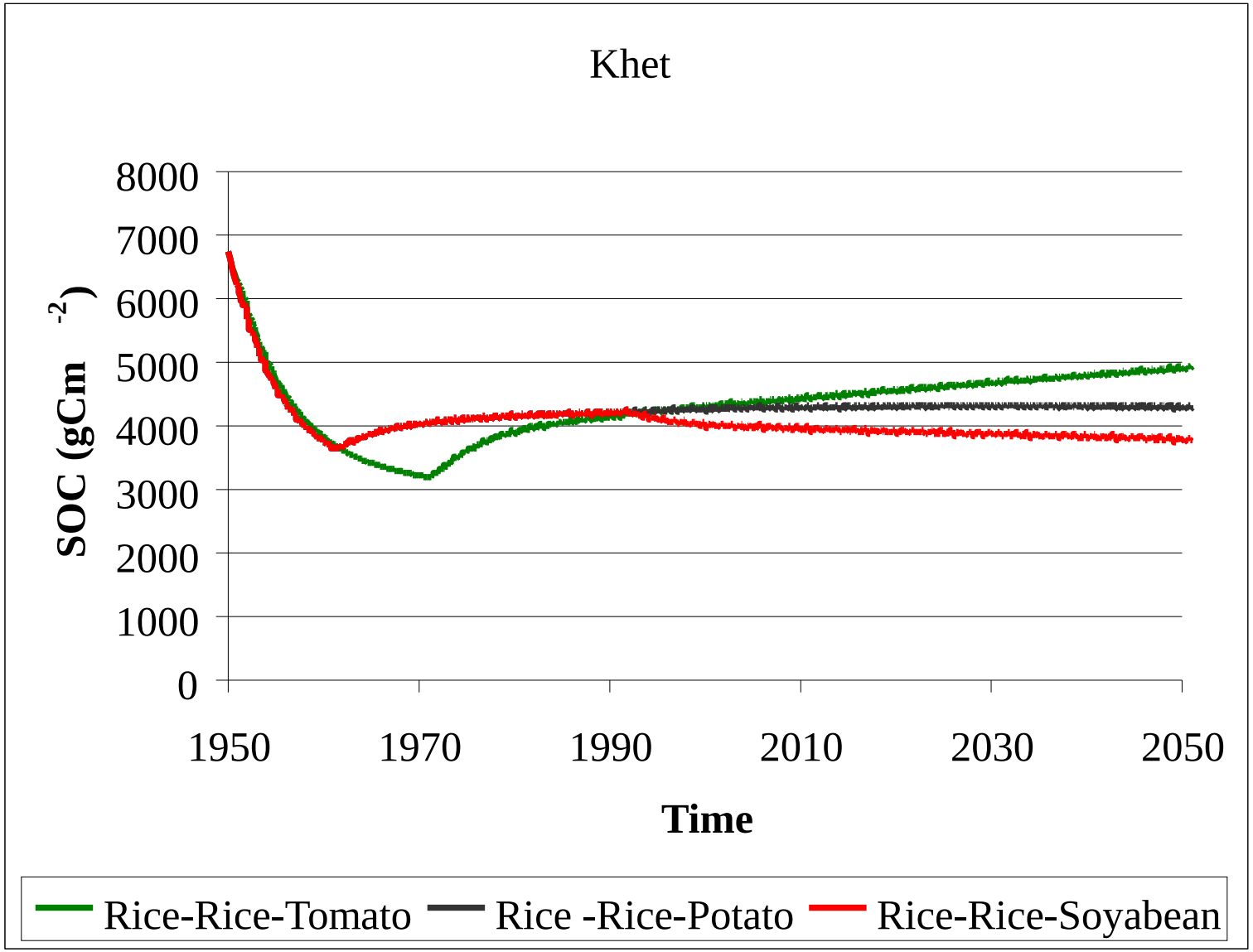


Figure 2. Soil organic C pool in irrigated low land (Khet) under three different cropping system scenarios

Shrestha et al. (2009)

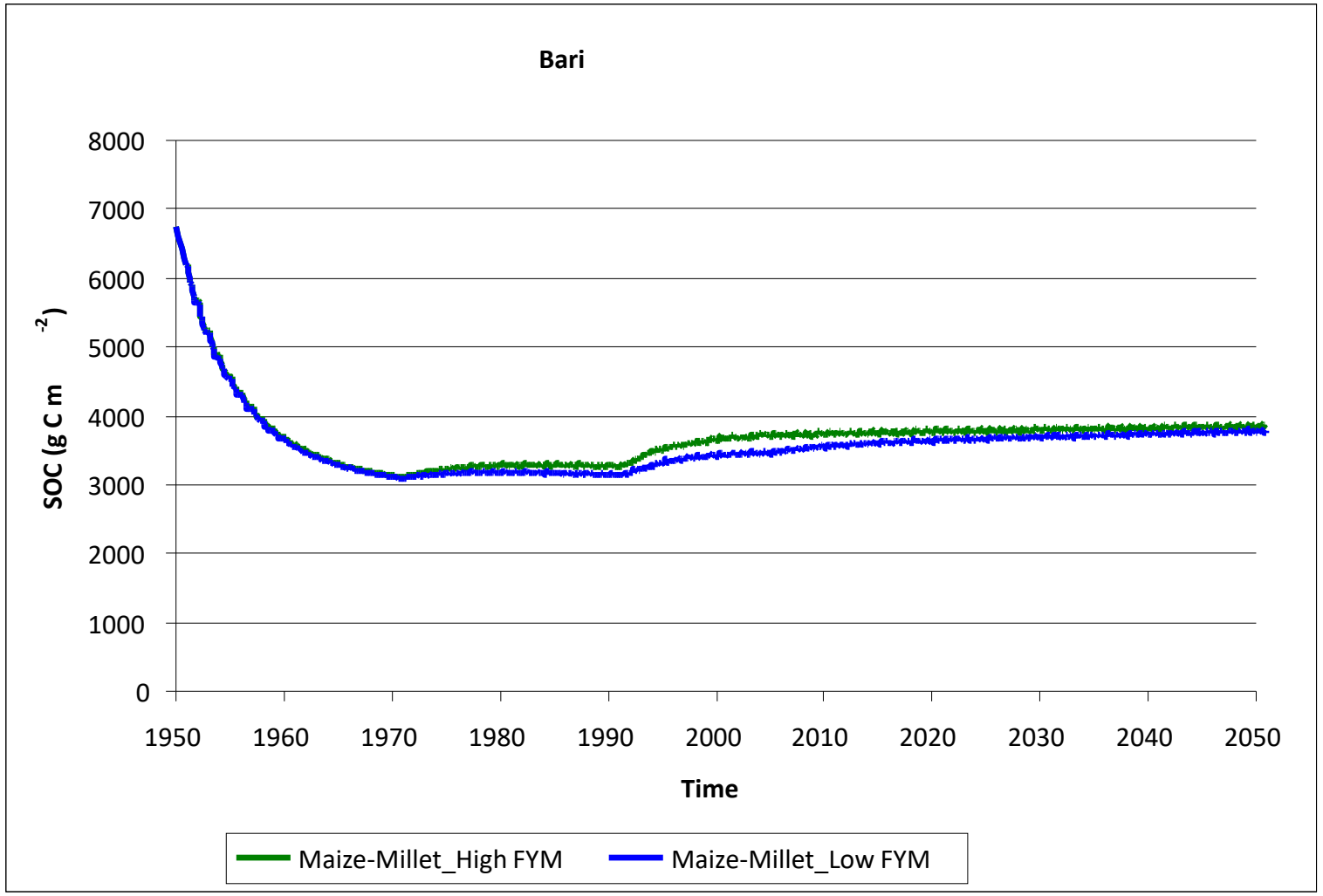


Figure 3: Soil organic C pool in rain fed upland Bari cropping under different rates of farm yard manure (FYM high 5.0 Mg ha-1, low 3.6 Mg ha-1) application scenarios.

Shrestha et al. (2009)

Effect of Climate Change on SOC Pool

Climate change scenario assumed- temperature increase of 2.3ºC and 1.9ºC for Dec-May and Jun-Nov, respectively, with corresponding rainfall increment of 15 and 23%, respectively

(Agrawala et al., 2003).

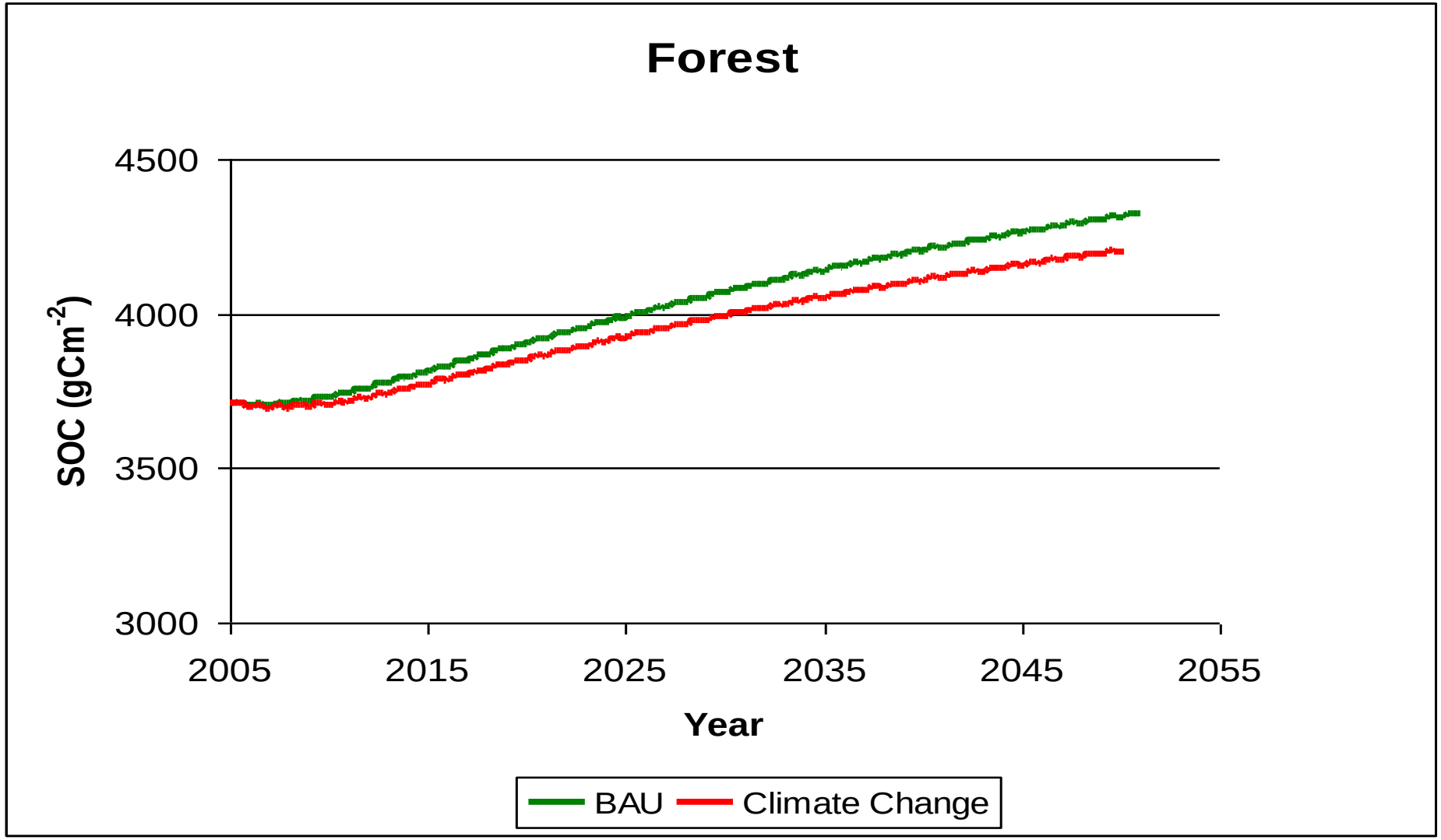


Figure 4: Soil organic C pool in forest soils in the projected period (2005-2050) under climate change scenarios with nominal erosion

Shrestha et al. (2009)

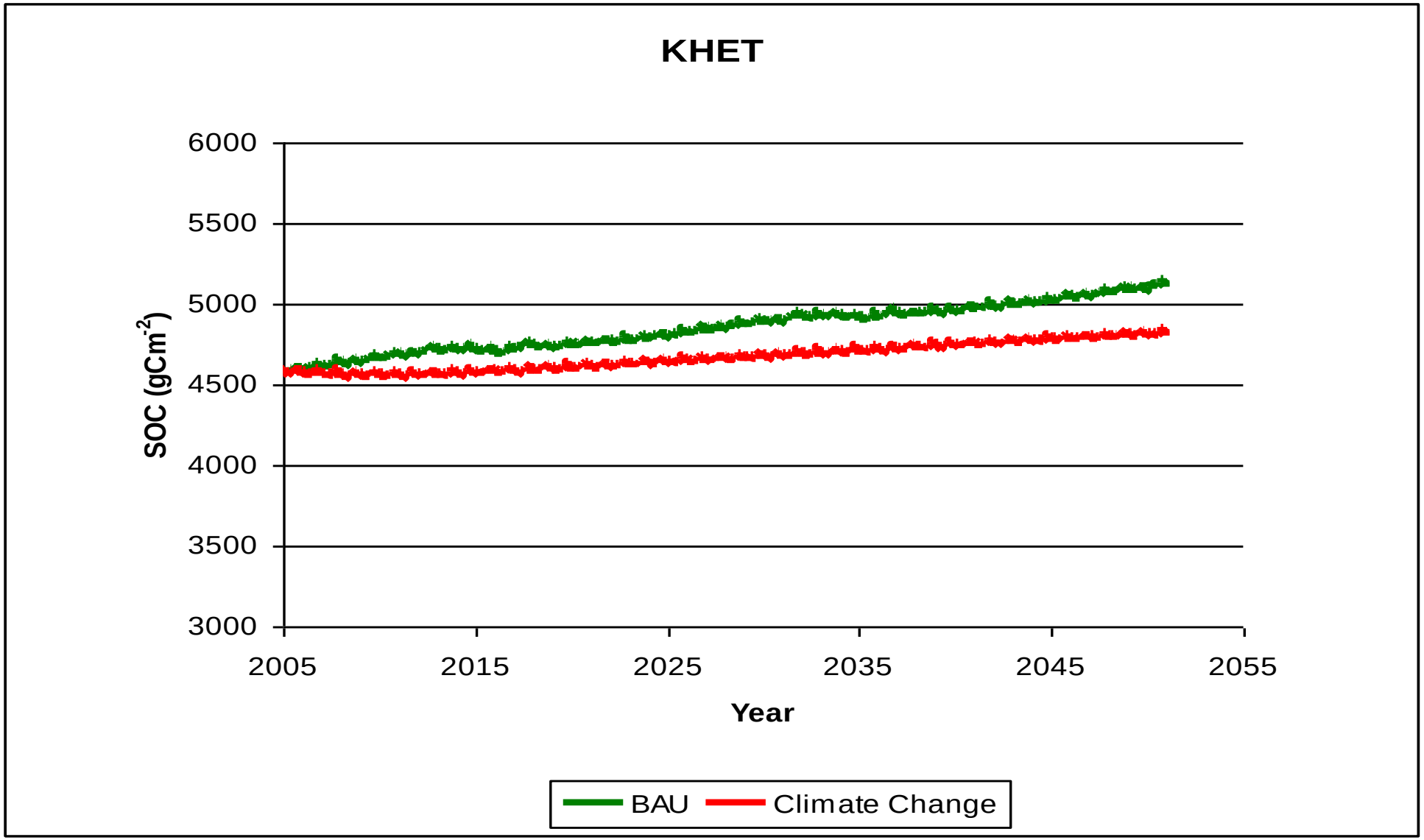


Figure 5a. Soil organic C pool in Khet soils in the projected period (2005-2050) under climate change scenario and BAU

Shrestha et al. (2009)

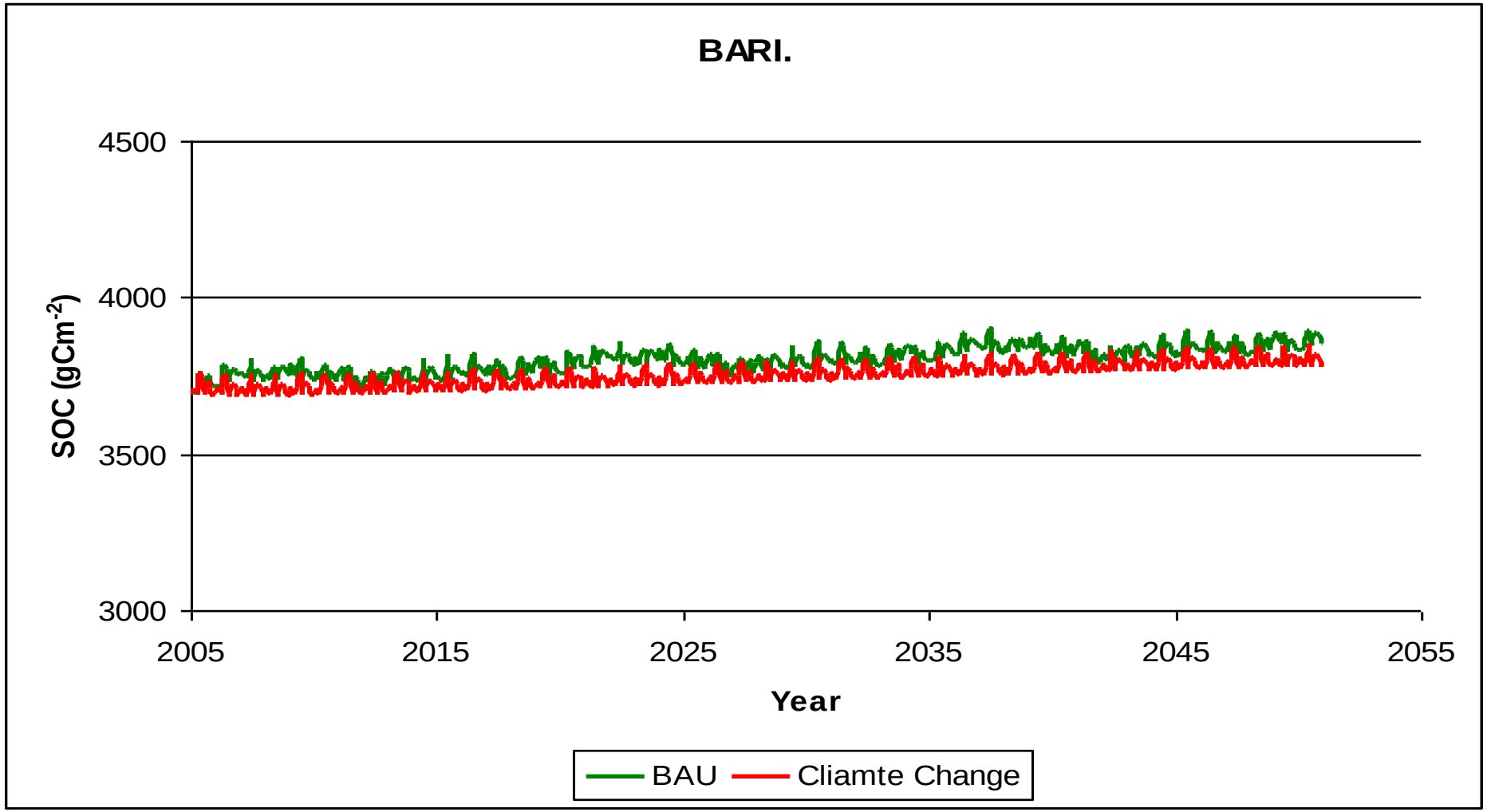


Figure 5b. Soil organic C pool in Bari soils in the projected period (2005-2050) under climate change scenario and BAU. Shrestha et al. (2009)

Table 4. Model and field estimated soil organic carbon pool (g C m^{-2}) under different land uses in different time periods

Land Uses	1976		1989		2004	
	Model	Field*	Model	Field*	Model	Field
Managed dense forest	3843.2	3484	3841.8	3484	3805.6	3836.3
Irrigated low land (*Khet*)	3738.1	3819	4147.3	3886	4377.2	3925.2
Rain fed upland (*Bari*)	3247.3	3551	3268	3819	3721.8	4211.1

*Estimated based on IPCC guideline

Shrestha et al. (2009)

Conclusion

- The Century model performed well in its representation of the effects of various land management systems.
- Simulation results showed significant loss of C from the system in the first temporal block under all land uses.
- However, C was maintained or improved later under improved management.

Conclusion

- **Potential for partial recovery under improved forest management, and in the cultivated soils is due largely to manure additions and cropping management systems.**

- **Potential negative impacts of climate change were demonstrated clearly.**