Climate Change Impacts on Three Key Soil Properties in New South Wales

2nd edition

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Front cover: Rural landscape, Merriwa Plateau, NSW. Photo: X Yang and J Gray/OEH

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Abbreviations

BoM	Bureau of Meteorology
CCC	CCCMA31: a global climate model developed by the Canadian Centre for Climate Modelling and Analysis
CSIRO	Commonwealth Scientific and Industrial Research Organisation; CSIRO_MK30 is a global climate model developed by CSIRO and BoM
DSMM	digital soil modelling and mapping
ECHAM	ECHAM5: a global climate model developed by the Max Planck Institute for Meteorology, Germany
GIS	geographical information system
MIROC	MIROC32 (Model for Interdisciplinary Research on Climate): a global climate model developed in Japan by several institutions
N	total nitrogen
NARCliM	NSW and ACT Regional Climate Modelling project
OC	organic carbon
P	phosphorous
pH	a measure of acidity or alkalinity (see Glossary)
RMSE	root mean square error
SALIS	Soil and Land Information System
SCARP	Australian Soil Carbon Research Program
SLGA	Soil and Landscape Grid of Australia
SOC	soil organic carbon

Summary

Climate change has the potential to have significant impacts on the soils of New South Wales, affecting agricultural productivity and ecosystem health across the State. This study used digital soil modelling and mapping techniques to examine potential changes in three key soil properties – soil organic carbon (SOC), pH and sum-of-bases (a subset of soil macro-nutrients) – due to projected climate change over New South Wales in the coming decades.

Twelve climate change models were applied, representing four global models downscaled with three regional models and sourced from the NSW and ACT Regional Climate Modelling (NARCliM) project. Changes were predicted over 'near' and 'far' change periods (to approximately 2030 and 2070 respectively). Considerable variation in the extent of change in the three soil properties was demonstrated between the different climate models, but the directions of change were generally consistent apart from a few exceptions. Using averaged results from the 12 models, changes for the three properties across the State over two broad soil depth intervals (0 to 30cm and 30 to 100cm) were derived. These represent the change from climate change alone, and do not consider the influence of ongoing or evolving land management practices.

- SOC stocks are projected to decline over the State, typically varying between 0 to 10 tonnes per hectare (t/ha) loss but reaching a maximum decline of over 20t/ha in the southern alpine region.
- An increase in pH (i.e. becoming more alkaline) is projected over the State, generally increasing from east to west (not considering influence of ongoing land management which may contribute to acidification). The southern alpine region displays the greatest increases of up to 0.5 pH units or more.
- An increase in sum-of-bases (subset of macro-nutrients) is projected over the State, typically varying between 5 and 20%. As for pH, there is a general increase from east to west and in higher areas (not considering ongoing land management, which may contribute to nutrient decline). The far southern alpine regions display the greatest increases of up to 30% or more.

Changes in these soil properties may affect both agricultural and natural ecosystems. Soil condition, and the associated agricultural productivity and ecosystem health, generally declines with reduced organic content due to a decline in physical, chemical and biological attributes. Even slight changes in pH and macro-nutrient content can directly affect plant growth – both positively and negatively - in both agricultural and native systems, as many plants have narrow chemical tolerance ranges. Changes in these soil properties may signify changes in other important minor and trace elements, which may also have major potential impacts.

Ongoing land management practices over agricultural lands were not considered in this analysis, but these may also have an impact on soil properties. For example, agricultural induced acidification may override the trend towards alkalinity projected in this analysis. Native ecosystems will be more vulnerable to the projected soil changes, particularly in alpine regions, where there is less potential for the migration of current ecosystems to areas with suitable soil conditions.

The results for SOC also have implications for climate change mitigation programs that are based upon increased soil carbon sequestration. The predicted decline in soil carbon storage levels across almost the entire State suggests even greater carbon-enhancing actions will be required to produce the desired soil carbon increases.

Despite several potential weaknesses and sources of uncertainty in the modelling process, the results provide a useful first approximation of changes in important soil properties arising from projected climate change and can help guide the management of agricultural and native landscapes in New South Wales over the coming decades.

1. Introduction

Climate change has the potential to have a significant impact on soils. Soils support the growth of most plant life and are a crucial element of all terrestrial ecosystems. The physical and chemical characteristics of soils have a great influence on the type of vegetation that can be supported and on the agricultural potential of land. Knowledge of soil attributes is an essential input into many environmental modelling systems, including climate change, ecological, agricultural and hydrological models.

Many soil properties are sensitive to climate variables such as rainfall and temperature. It is important to understand the potential changes that may occur in key soil properties over New South Wales because of changes in these properties associated with predicted climate change over the coming decades. Three soil properties that deserve examination in this respect are soil organic carbon (SOC), pH (i.e. the degree of soil acidity or alkalinity) and sum-of-bases (i.e. a subset of common macro-nutrients: calcium, magnesium, potassium and sodium), as these are key soil chemical attributes that influence agricultural and native ecosystem characteristics. Changes in these properties may affect agricultural productivity and ecosystem health across the State. They may result in changes in species distribution and abundance at local, regional and statewide scales. Furthermore, the potential of soil to sequester or release carbon is important for assessing climate change mitigation strategies (Lal 2004; Wilson et al. 2011; Baldock et al. 2012). SOC and pH change are considered priorities for national soil monitoring programs (McKenzie & Dixon 2006).

In this project, we used digital soil modelling and mapping (DSMM) techniques (as defined in the Glossary) to examine potential changes in these three key soil properties after application of a range of climate change models sourced from the NSW and ACT Regional Climate Modelling (NARCliM) project. Specific aims were to:

- prepare tabulated data and spatial maps on the absolute and/or relative changes in SOC, pH and sum-of-bases (common macro-nutrients) over New South Wales over two time intervals (centred around 2000 to 2030 and 2000 to 2070) by using the NARCliM climate models
- examine the trends in soil property changes according to environmental subclasses based on current climate – parent material (soil type) and land use zones
- examine soil property changes with respect to NSW State planning regions.

1.1 Previous work

The response of soils to external environmental factors has long been recognised (Dokuchaev 1899; Jenny 1941). Although the effects of climate and climate change on soils have been examined and modelled broadly, in New South Wales and Australia (OEH 2011; Baldock et al. 2012) and elsewhere (Jenny 1980; Lal & Follett 2009; Ostle et al. 2009), relatively few studies have developed extensive spatial predictions of changes in soil properties under formal climate change projections. Studies that have been reported are focused primarily on changes to SOC, reflecting its importance to climate change modelling and mitigation strategies. Most of these studies have applied simulation modelling approaches such as the carbon dynamics simulation models of RothC (Coleman & Jenkinson 1999), Century (Parton & Rasmussen 1994) and SOCRATES (Grace et al. 2006).

A global study by Gottschalk et al. (2012) suggested an overall global increase in SOC stocks by 2100 under all the climate models and emission scenarios they studied, but the extent of increase varied with different models and scenarios. However, large variations in both the direction and extent of SOC change occurred over different regions of the globe, with higher latitude regions undergoing overall losses but tropical regions undergoing overall gains. Similar broad findings were reported by Yurova et al. (2010).

At the country or regional level, SOC change under climate change has been spatially modelled in several recent studies. In Australia, Luo et al. (2019) examined carbon change over rainfed cropping areas to 2070. In North America these include studies over the Everglades of South Florida to 2060 (Orem et al. 2015); Californian rangelands to 2100 (Byrd et al. 2015); the entire state of Louisiana to 2100 (Zhong & Xu 2014); an experimental forest in New Hampshire to 2100 (Dib et al. 2014), the US Great Plains over the next 30 years (Follett et al. 2012) and Canada to 2099 (Smith et al. 2009). In Asia, studies have been undertaken over parts of the Tibetan Plateau and all of Mongolia (Zhao et al. 2013, 2015) and in Japanese forests to 2099 (Hashimoto et al. 2012). In Europe there have been studies over north-eastern Spain to 2087 (Alvaro-Fuentes et al. 2012) and the semi-arid Mediterranean agro-ecosystems to 2100 (Alvaro-Fuentes & Paustian 2011).

The impact of projected climate change on other soil properties relating to fertility such as pH or macro-nutrients appears to have been rarely covered in the literature. Total nitrogen (N) and available phosphorus (P) were included with SOC in the study by Orem et al. (2015) over southern Florida. Changes to soil fertility and impacts on cereal crop yields in Mexico to 2100 were examined by Nikolskii et al. (2010). Also, in Mexico, Castillo-Alvarez et al. (2007) reported changes in an integrated fertility index and an increase in maize yields in arid and semi-arid zones, but a decrease in humid and semi-humid zones. Sirotenko et al. (1997) reported a potential doubling of cereal crop yields in the steppe regions of Russia as a result of climate change and associated changes in soil chemistry.

There appears to have been very limited use of DSMM approaches to the prediction of soil property changes under climate change, as adopted in this study. DSMM approaches use data mining and statistical techniques to predict soil properties by using a range of environmental covariates (McBratney et al. 2003). They have been used widely to predict and spatially map soil properties under present day conditions around the world (Grunwald 2009; Minasny et al. 2013), including in Australia, as evidenced by the recent release of the Soil and Landscape Grid of Australia (Grundy et al. 2015), which includes maps of current SOC and pH, among other soil properties. Also, for Australia, digital maps have recently been produced for present day SOC by Bui et al. (2009) and Viscarra Rossel et al. (2014) and for present day pH, total N and total P and other properties by Henderson et al. (2005).

A rare example of the use of a DSMM approach to examine soil property changes under climate change was the study by Minasny et al. (2013), who derived a map of SOC change over southern New South Wales under projected climate change with a high emission scenario to 2030 and revealed an average decline of 5 t/ha of carbon over the region. A space-time modelling framework called STEP-AWBH that facilitates DSMM estimates of soil property change under changing climate, land use or other environmental variables has also recently been proposed by Grunwald et al. (2011). Baldock et al. (2012) discussed the processes, potential impacts and ongoing research needs associated with changes in SOC and soil nitrogen arising from climate change in Australia.

2. Assessment methodology

This project used a digital soil modelling and mapping approach. It started with compilation of the required soil property dataset and environmental grids representing soil forming factors over New South Wales, which included current climate data from the Bureau of Meteorology (BoM) representing the period 1961 to 1990. Statistical models were then developed for each soil property; these effectively modelled soil conditions over the BoM climate data period.

NARCliM's projected climate grids over three epochs (1990–2009, 2020–2039 and 2060–2079) were then substituted for the BoM climate data into these models to prepare predictive maps of soil properties over New South Wales under these projected climate conditions. By comparing the predicted future soil property maps with current maps, the extent of change in these properties was derived. The changes were then further analysed, with breakdown according to current climate - parent material - land use subclasses, and by State planning region.

2.1 Soil profile dataset

Data for the three soil properties was derived from the NSW Soil and Land Information System (SALIS), representing soil data collected over New South Wales mostly between 1970 and 2013. An exception was for the upper 30cm layer for SOC that used data from the 2008 NSW Monitoring Evaluation and Reporting program (MER) (Chapman et al. 2011; OEH 2014) and the Australian Soil Carbon Research Program (SCARP) (Sanderman et al. 2011), because of stronger modelling performance and the availability of bulk density measurements (allowing for estimates of SOC stocks).

Only those profiles with laboratory soil property data, plus parent material and topographic descriptors that could be reliably classified, were used for the final analysis. The final dataset contained over 5000 points, although numbers of samples varied for the different properties. Figure 1 shows the locations of profile points across the State. Values reported for each soil horizon over the entire original dataset were converted into two standard depth intervals - 0 to 30cm and 30 to 100cm - by using the equal-area splining process of Bishop et al. (1999).

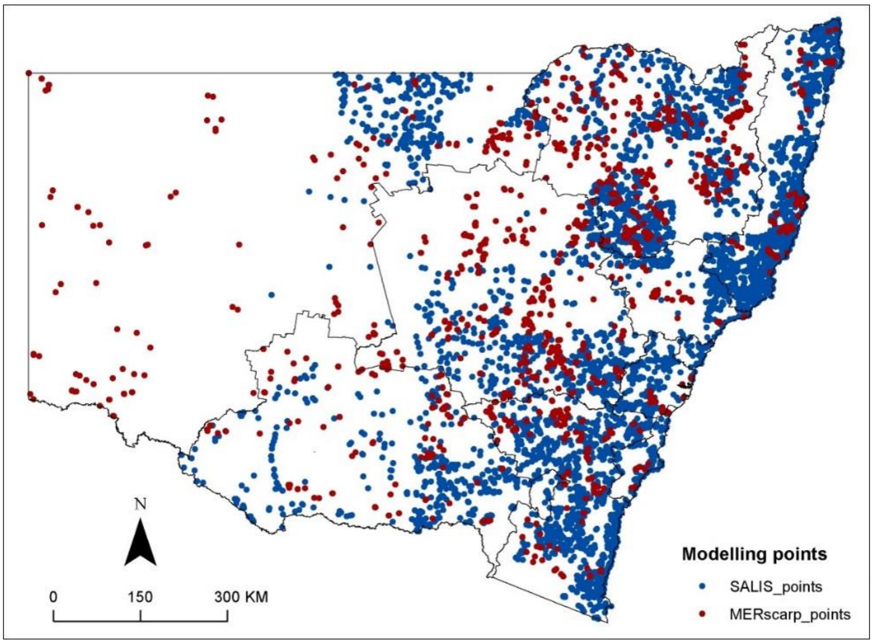

Figure 1 Locations of modelling profile points

2.2 Soil properties

The three key soil properties of organic carbon, pH and sum-of-bases were examined. These properties are all important indicators of a soil's chemical and physical characteristics and condition and, more broadly, are vital for a soil's agricultural productivity and ecosystem health.

SOC is perhaps the most widely used indicator of a soil's health. In NSW topsoils, it normally varies between 0.4% and 3% but extends to over 12% in organic soils, depending on the soil and environmental conditions (Hazelton & Murphy 2007). These concentrations equate to topsoil stocks of less than 10 to over 100t/ha. SOC is associated with many chemically and physically desirable attributes, including high biological activity, nutrient availability, soil physical structure, water-holding capacity and aeration (McKenzie & Dixon 2006; Baldock et al. 2012; Murphy 2015).

The pH of a soil represents the degree of acidity or alkalinity. In this report, all pH values refer to values measured in calcium chloride, which are typically 0.5 to 1.0 units less than those measured in water (Hazelton & Murphy 2007). Most agricultural plants are suited to $pH_{(CaCl_2)}$ ranges between 4.5 to 8.0 (NSW Agriculture 2000). All plants however, including both agricultural and native vegetation species, have pH suitability ranges, beyond which they will suffer. Some plants have a broad range, whereas others may have a relatively narrow range. pH levels also influence the availability of nutrients and toxic elements, which also affects plant growth.

The soil property of 'sum-of-bases' represents the concentration of a subset of common macro-nutrients and is formally defined as the sum of the calcium, magnesium, potassium and sodium cations in the fine fraction (<2mm) of the soil. It does not include other important nutrients such as phosphorous, nitrogen, sulphur etc. Values typically range from less than 5 to greater than $40cmol_c$/kg (Hazelton and Murphy 2007). Higher levels of macro-nutrients are normally indicative of higher-fertility soils and greater agricultural productivity (McKenzie et al. 2004; Charman 2007), although high levels of sodium can have deleterious effects (Hazelton & Murphy 2007). Different plants – both agricultural and native vegetation species – have differing requirements and tolerances of macro-nutrients. Substantial changes in macro-nutrients can be indicative of important changes in other minor and trace elements, which equally can have major impacts on plant growth.

SOC is also important for its role in climate change modelling and the potential to contribute to climate change mitigation programs. Changes in the quantity of carbon stored in the soil can affect the global carbon cycle and alter carbon levels present in the atmosphere as carbon dioxide (Lal 2004; Wilson et al. 2011; Baldock et al. 2012). Thus, increases in soil carbon may correspond to lowering greenhouse gas levels in the atmosphere and thereby enhance climate change mitigation programs. Alternatively, decreases in soil carbon may exacerbate climate change.

The laboratory test methods used for these three soil properties and the numbers of samples in the final modelling dataset are given in Table 1.

Table 1 Soil properties: laboratory methods and final sample numbers

Soil property	Units	Laboratory method (test numbers from Rayment & Lyons 2010)	No. of samples
SOC	%	LECO combustion; Walkley Black wet oxidation (C6A/2)	1473[1]
	tonnes/ha	Bulk density: P14A or similar core method (mass of known volume)	1521[2]
pH_{CaCl_2}	pH units	pH of 1:5 soil/0.01M calcium chloride extract (C2B/2). Includes conversions from pH 1:5 soil/water suspension (C2A/2)	4692
Sum of bases[3]	$cmol_c$/kg	C5A/4 silver thiourea and C5B/1C ammonuim choride	2951

[1] SOC from MER and SCARP programs (0–30cm)

[2] SOC from SALIS (30–100cm)

[3] Ca, Mg, Na and K

Variation in different laboratory methods for the same soil property, owing to differences in the dates and laboratories of the analyses, results in a degree of inconsistency in the test results. This represents a source of potential error in the predictive models. The Walkley-Black method has been reported to underestimate total SOC levels (Skjemstad 2000), but as there is much uncertainty regarding the most appropriate correction factor (Bui et al. 2009; Conyers et al. 2011) no correction factor was applied. Final analysis excluded samples with less than 0.1% organic carbon (OC) (as these were considered unreliable) and greater than 18% OC (as these are always defined as organic materials in the Australian Soil Classification [Isbell 2002] and can distort modelling relationships). Organic carbon stocks (t/ha) was derived, in addition to concentration (%), after we had accessed bulk density data from the *Soil and Landscape Grid of Australia*.

To avoid reporting two separate pH test results, pH_{water} values were converted into $pH_{(CaCl_2)}$ values by using the correlation tables of Henderson & Bui (2002). The latter mode is preferred in Australia as it more closely represents the ionic soil solutions typically found in the field and thus gives more reliable results.

2.3 Covariates

Covariates were selected to represent the key soil-forming factors of climate, parent material, relief and biota, as outlined below.

Current climate

For preparation of initial statistical models:

- *Mean annual rainfall* (mm/year) – derived from BoM 2.5km Australia wide climate grids from the Australian BoM, with interpolation of cell values down to a 100m grid (using ArcGIS interpolation spline tool), to represent mean values obtained over the 1961 to 1990 period.
- *Mean annual daily maximum temperature* (°C) - refers to the mean of daily maximum temperatures over the year and was derived from the above BoM source.

For preparation of output grids under climate change:

- NARCliM climate grids for *mean annual rainfall* and *mean annual daily maximum temperature* across New South Wales over the three periods - 1990–2009, 2020–2039 and 2060–2079 - were accessed. These were derived from the NARCliM project (Evans et al. 2014) covering 12 simulations, namely four global models: CCCMA3.1, CSIRO_MK30, ECHAM5, MIROC3.2, each downscaled with three regional models R1, R2 and R3. These are described further in Section 3: Supporting information.

The initial grids were 0.1 or 10km but were interpolated down to 100m rasters by using the ArcGIS interpolation spline tool. Checks were done to make sure the process was not attempting to predict outside the bounds of the current climate (e.g. mean annual daily maximum temperature above 35ºC).

Parent material

- *Silica index (lithology class)* – an index representing the lithological characteristics of the parent material (Gray et al. 2015b, 2016). It denotes the assumed approximate silica (SiO_2) content of different parent materials, with increasing silica being associated with higher quartz content and lower chemical fertility. For example, granite belongs to the moderately siliceous lithological class, with an approximate silica content of 73%, whereas basalt belongs to the mafic class, with an approximate silica content of 48%. Further examples are provided in Table 3. Parent material descriptors recorded at each site were used to derive the silica indices for model development, but the 1:250 000 NSW Geological Survey polygonal geology map was used for the final maps.
- *Radiometrics* – gamma radiometric potassium, uranium and thorium; 90m grids developed by and sourced from Geoscience Australia were used.

Relief

- *Topo-slope index* – an index that can be derived from field observations and combines topographic position and slope gradient. The 1 to 6 scale represents the degree to which a site is subject to depletion or accumulation of water, soil particles and chemical materials (Gray et al. 2015b). Model development relied on soil survey site data for individual sites; map development used a 100m digital elevation model to derive slope % and a topographic position index (Jenness 2006) 90m grid derived from the *Soil and Landscape Grid of Australia* (Grundy et al. 2015).
- *Topographic wetness index* – a widely used index that represents potential hydrological conditions based on slope and catchment area, as derived from digital elevation models. A 90m grid was accessed from the *Soil and Landscape Grid of Australia.*
- *Slope* – slope gradient in percent, as derived from a 100m digital elevation model.
- *Aspect index* – an index used to represent the amount of solar radiation received by sites, ranging from 1 for gentle north- or north-west-facing slopes to 10 for steep south and south-east slopes (Gray et al. 2015b). The index was derived from a 100m digital elevation model with a 90m aspect grid from the *Soil and Landscape Grid of Australia*.

Age

- *Weathering index* – an index used to represent the degree of weathering of parent materials (Wilford 2012). A 90m grid was accessed from Geoscience Australia.

Biota

- *Land disturbance index* – an index that reflects the intensity of disturbance associated with land use (from 1: natural ecosystem to 6: intensive cropping) (Gray et al. 2015b, modified from NCST 2009). For model development, site land use was taken from field profile descriptions; for map development it was derived from 1:25 000-scale polygonal land use mapping (OEH 2007). The modelling assumed no change from current land use, which represents a limitation of the study, as landholders will likely adapt their land use and management in response to changing climate and soil properties.

Note that a ground cover variable (such as MODIS fractional cover) was not included as it is markedly correlated with climate and would not have remained constant into the future with the projected climate change, as required for the modelling, thus potentially distorting the modelling results.

2.4 Model development and statistical analysis

Analysis was performed with R statistical software (R Core Team 2013). The soil dataset was apportioned 80% as training data and 20% as validation data, with modelling using multiple linear regression. A natural log transformation was applied to the SOC (both % and mass) and sum-of-bases values to address the observed skewness in the response.

The models for each depth interval were validated by using the validation datasets. Lin's concordance correlation coefficient was used to measure the level of agreement of predicted values with observed values, relative to the 1:1 line (Lin 1989). Also determined were the root mean square error (RMSE) and mean error (Table 2).

The multiple linear regression models were applied to the covariate grids to prepare maps over New South Wales for each soil property at each depth interval for each of the three time periods in a 'space for time substitution' process (Pickett 1989). The maps were replicated by using all 12 climate model grids. Thus, for each soil property there were maps for two depths, three time periods and 12 climate model grids, giving 72 maps for each property.

Absolute and/or relative changes in the three soil properties over the three time periods were derived by calculating differences over each pixel between the different layers (using a geographic information system [GIS] raster calculator). This was performed for each of the 12 climate models, and for their mean, to elucidate the varying impacts of the different climate models. In addition to presenting results over the entire area, the data were partitioned according to current climate - parent material - land use subclasses to observe the degree of response in different environmental regimes. Plots were prepared showing the mean and 90% confidence interval (being 1.645 x the standard error) for each subclass based on the 12 climate change models, as revealed by the GIS results. The mean results were also partitioned according to NSW State planning regions (Figure 2).

Changes were expressed in absolute terms for SOC and pH, but in relative terms (% change) for sum-of-bases, which was more meaningful given the high variation in initial base levels of different soils, (eg, approximately 5cmol$_c$/kg for a sandy soil compared to approximately 80cmol$_c$/kg for a dark clay soil).

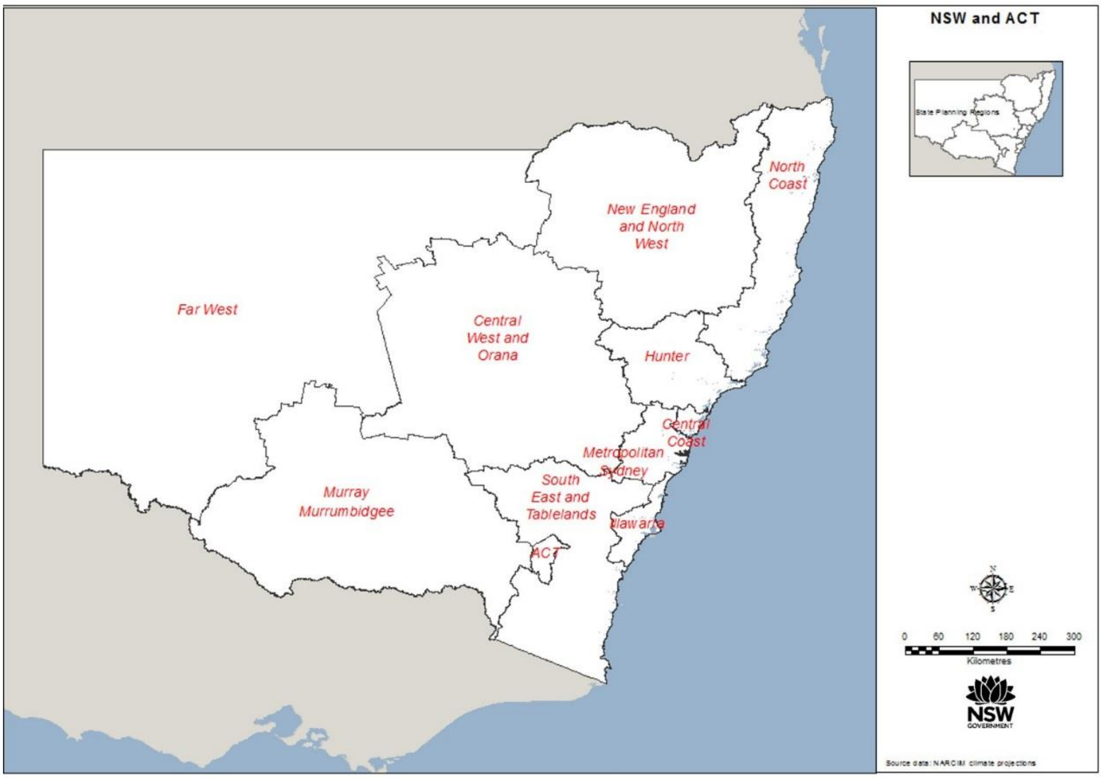

Figure 2 State planning regions of New South Wales

Table 2 Validation statistics of multiple linear regression models

Soil property	Depth interval (cm)	N	Lin's concordance correlation coefficient	RMSE	ME
SOC (log t/ha)					
	0–30	310	0.56	0.35	0.045
	30–100	307	0.25	0.65	-0.067
pH					
	0–30	938	0.66	0.78	0.019
	30–100	697	0.74	0.90	0.016
Sum-of-bases					
(log $cmol_c$/kg)	0–30	590	0.68	0.73	0.0077
	30–100	531	0.72	0.80	0.0044

N: sample number
RMSE: root mean square error
ME: mean error (prediction – observed)

3. Supporting information

3.1 Soils and physiographic character of New South Wales

New South Wales has a wide range of soil types, ranging from low to high plant-growth productivity and reflecting the wide range of parent material, climate and topographic conditions over the State. Figure 3 presents the soils of New South Wales according to the Australian Soil Classification scheme (Isbell 2002).

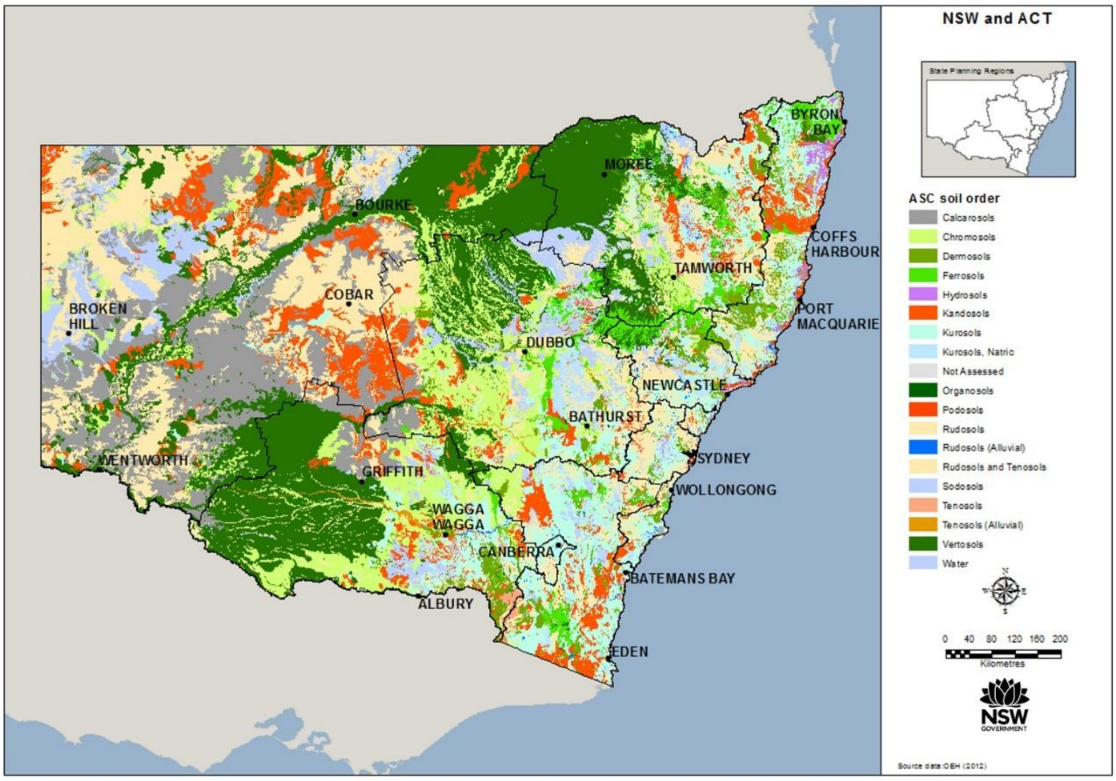

Figure 3 Soils of New South Wales

Source: OEH 2016

Low-fertility Tenosols and Kandosols are common over the highly siliceous parent materials (e.g. sandstones, granites and rhyolites) that are widespread throughout the State. Moderate-fertility soils such as Chromosols are common over intermediate and lower siliceous composition parent materials (e.g. granodiorites, trachytes and shales), particularly in the cereal belt of central New South Wales (Murphy et al. 2007). More fertile Dermosols, Ferrosols and Vertosols occur over intermediate and mafic parent materials (e.g. andesites and basalts), such as occur on parts of the Great Dividing Range associated with remnants of Cenozoic age (Oligocene/Miocene) volcanism and on the related alluvial plains. The higher-fertility soils typically have higher organic carbon, pH and macro-nutrient levels than the less fertile soils.

Detailed soil class mapping across much of the State has been done by OEH and predecessor agencies and is presented in published soil landscape reports available online: NSW soil maps. Recently, fine-scale digital soil mapping of individual soil properties across the State has been completed and released through OEH: Digital soil maps for key soil properties over New South Wales (OEH 2017), and also through the Soil and Landscape Grid of Australia (Grundy et al. 2015).

The association of soil types with four major parent material classes is summarised in Table 3. These zones are useful when combined with climate zones and major land use types to understand the distribution of soil types and their properties across the State and to better interpret the changes they may undergo because of climate change.

Table 3 Parent material classes and typically associated soils

Parent material class	Silica % (approx.)	Examples	Typical Australian Soil Classification soils
Siliceous – upper	>75	Quartz sands (alluvial and aeolian), pure quartzite, chert, quartz reefs, quartz sandstone and quartz siltstone	Quartzose Rudosols and Tenosols; Podosols
Siliceous – lower	65–75	Granite, rhyolite, adamellite, granodiorite, tonalite, quartz diorite, dacite, siliceous tuff, greywacke, feldspathic or lithic sandstone	Kandosols, base poor (low fertility) Chromosols, Kurosols and Sodosols
Intermediate	52–65	Trachyte, syenite, monzonite, diorite, andesite, low-quartz tuff, mudstone, argillaceous sediments (shale, etc.), alluvial grey and brown clays and most calcareous materials (e.g. limestone)	Dermosols; Ferrosols; grey and brown Vertosols; base rich (fertile) Chromosols, Kurosols and Sodosols
Mafic	≤52	Gabbro, dolerite, basalt, amphibolite, alluvial black cracking clay	Black Vertosols, Ferrosols

Based on Isbell et al. (1997); Gray & Murphy (1999) and Gray et al. (2016)

First approximations for common soil types only; most soil types will extend into adjoining parent material classes

The present-day distributions of the three key soil properties (SOC stocks, pH and sum-of-bases) over surface soil layers (0 to 30cm) across New South Wales are shown in Figures 4, 5 and 6. These form the most reliable baseline upon which modelled changes of soil properties can be based.

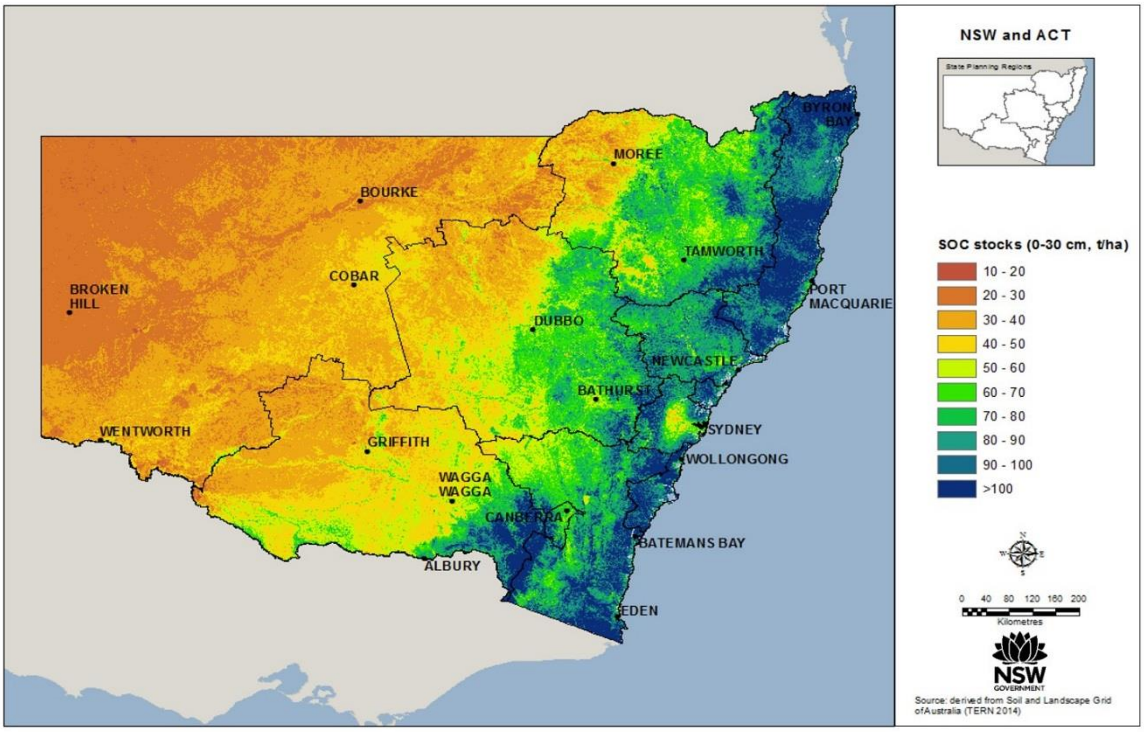

Figure 4 Organic carbon stocks over New South Wales (0 to 30cm soil depth)

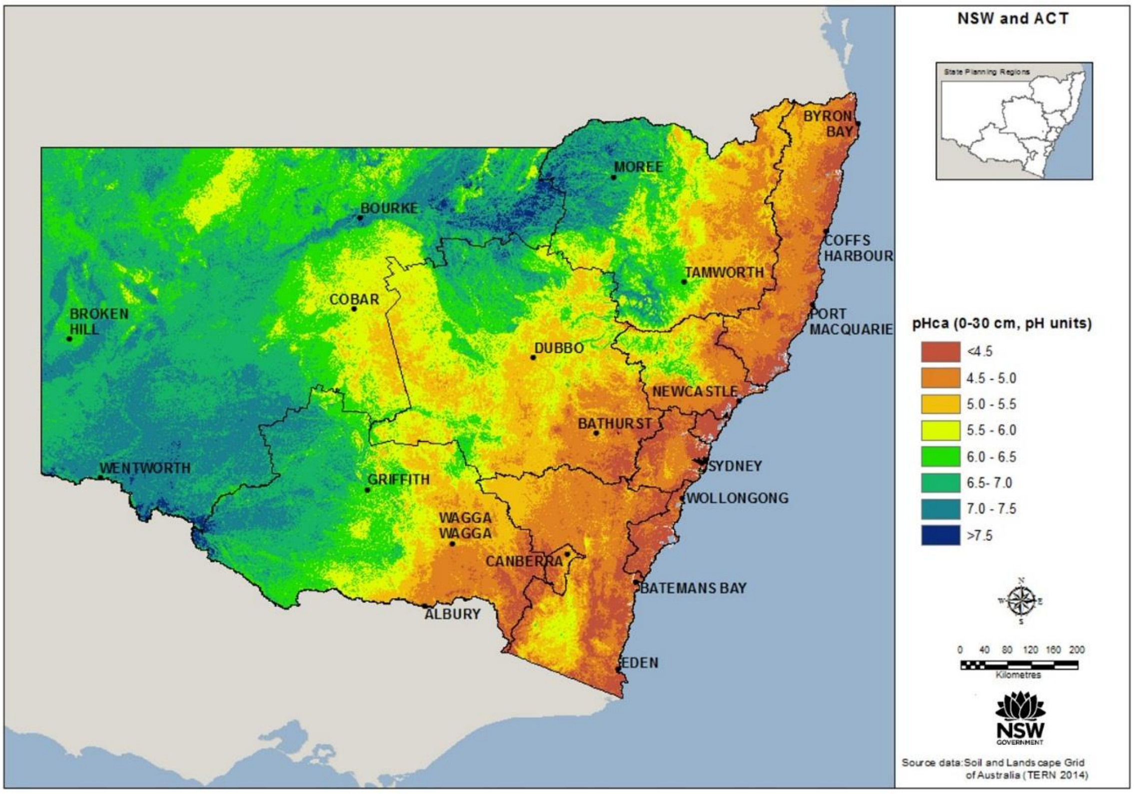

Figure 5 pH over New South Wales (0 to 30cm soil depth)

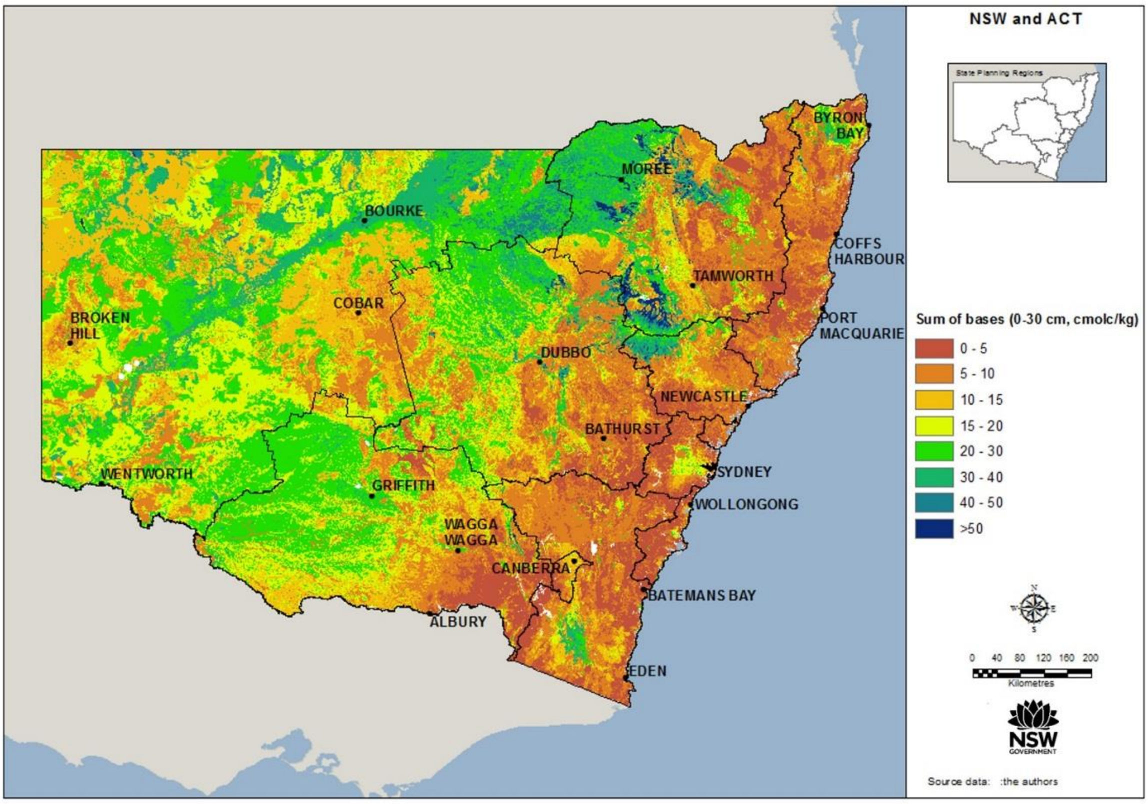

Figure 6 Sum-of-bases over New South Wales (0 to 30cm soil depth)

SOC stocks vary from less than 20t/ha in the far west of the State to greater than 100t/ha in the eastern highlands. Stocks generally increase in wetter, cooler conditions in soils derived from more mafic parent materials and under native vegetation.

The pH varies across the State from lower than 4.5 to higher than 8.0 pH units, with values increasing (i.e. becoming more alkaline) in drier (lower rainfall, higher temperature) conditions in soils derived from more mafic parent materials. The sum-of-bases (common macro-nutrients) ranges from almost zero up to higher than 50cmol$_c$/kg. It follows a similar distribution pattern to pH.

Climate is one of the major factors influencing these properties, so any changes in climate should be reflected in changes to these properties.

3.2 Baseline climate

Baseline climate data of mean daily annual maximum temperatures and mean annual rainfall have been gained from BoM 1961 to 1990 datasets and are presented in Figures 7 and 8.

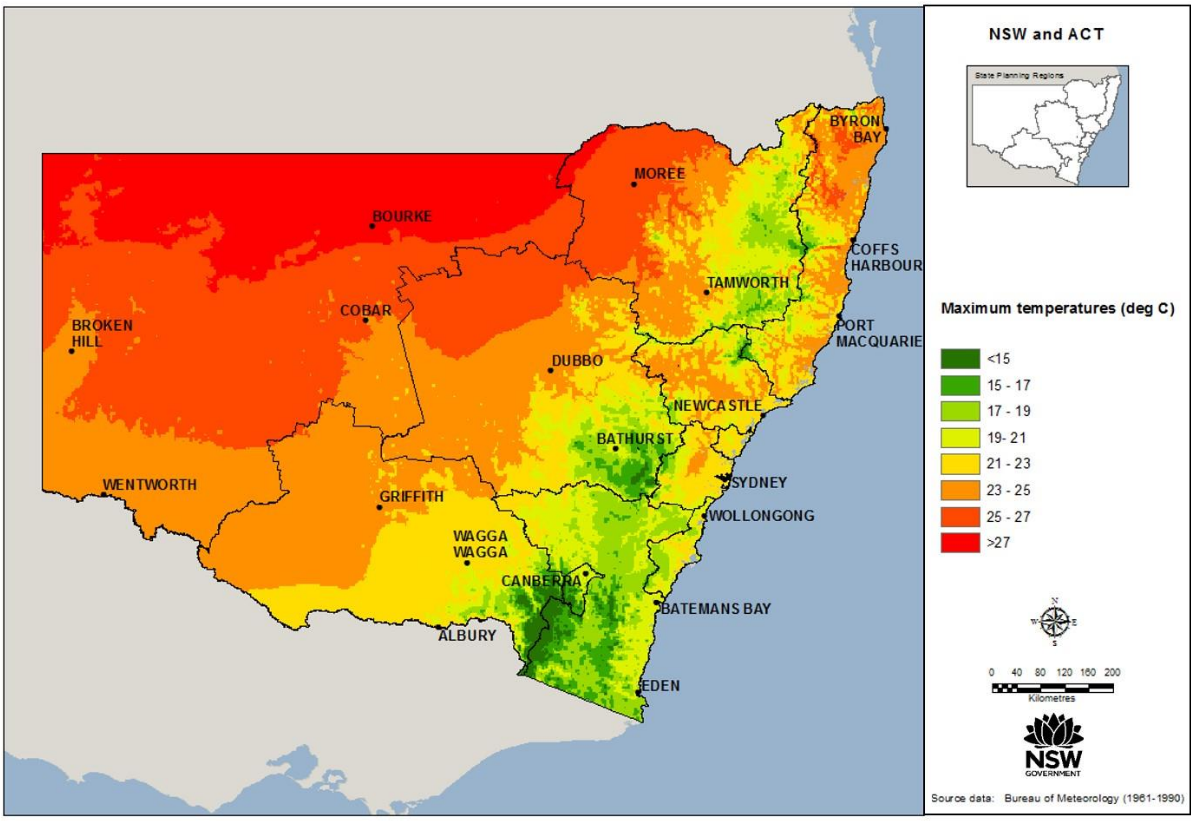

Figure 7 Mean daily annual maximum temperatures over New South Wales

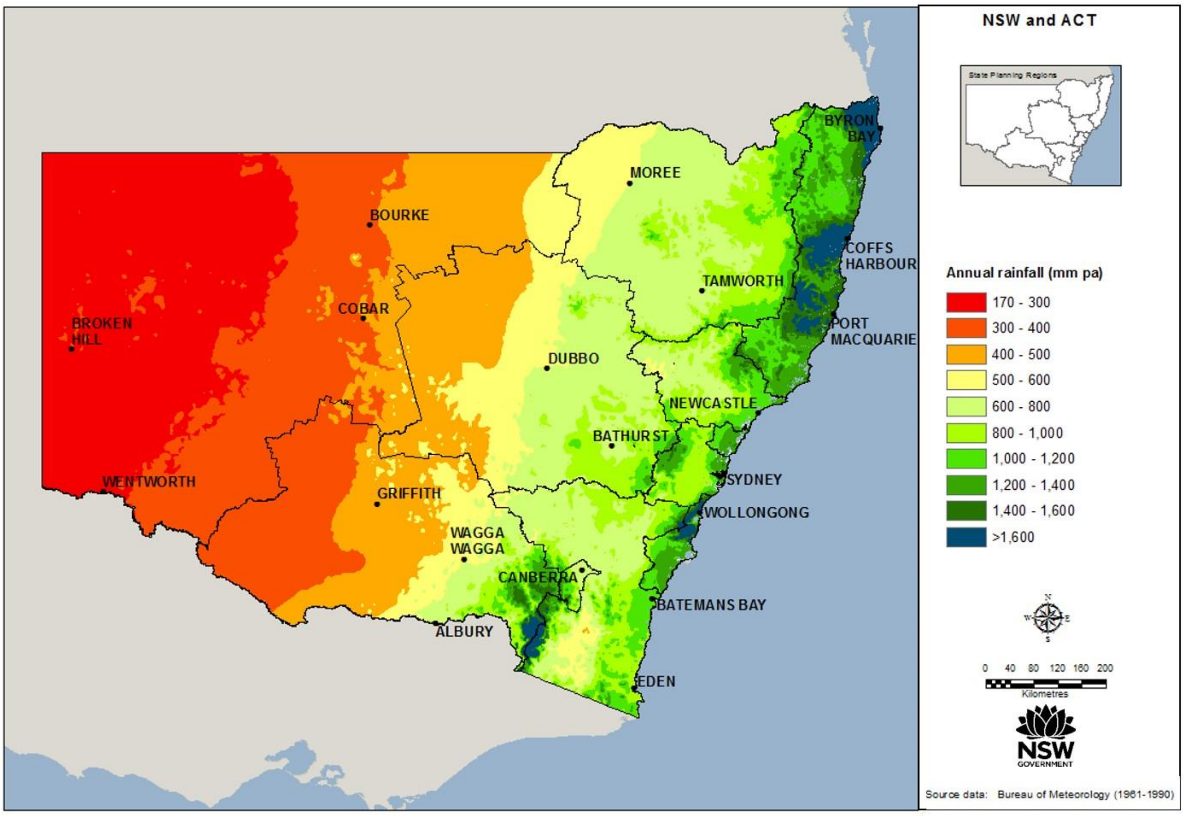

Figure 8 Mean annual rainfall over New South Wales

Mean annual daily maximum temperatures vary from a low of less than 15°C in the southern highlands region to a high of greater than 27°C in the north-western interior of the State. A broad pattern of increase moving north and to the interior is evident.

Annual rainfall varies from a low of less than 200mm/year in the far west of the State to a high of over 2000mm/year in the far north-east coastal ranges. There is a clear pattern of decline moving from east to west in the State.

For post-modelling interpretation purposes, current climate was grouped into three broad classes based on the ratio of these two climate variables (*Mean annual rainfall / Mean annual daily maximum temperature)*: dry <25; moist 25−50; wet >50 (Figure 9), a broad climate classification developed here for this project.

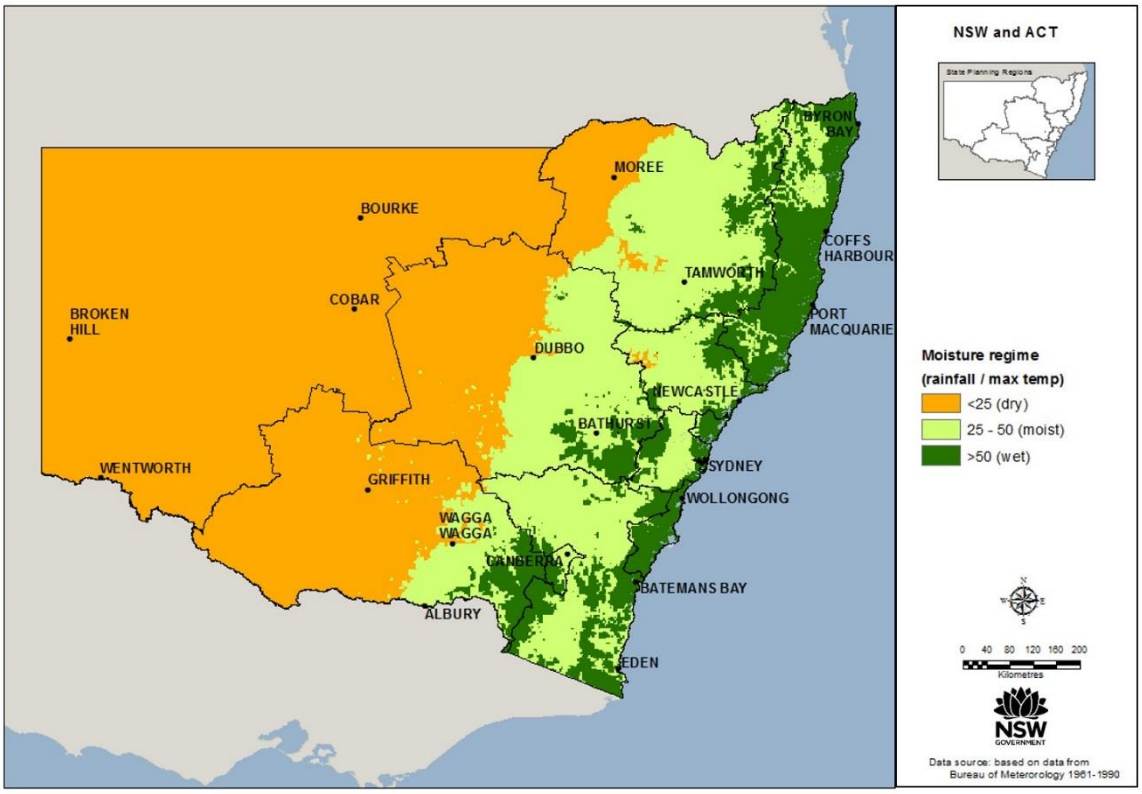

Figure 9 Moisture regimes (rainfall/maximum temperature) over New South Wales

3.3 NARCliM climate projections

The NARCliM climate projections over the three time periods (1990–2009, 2020–2039 and 2060–2079) are derived from 12 climate change models. These comprise four global models from the World Climate Research Program's (WCRP) Coupled Model Inter-comparison Project phase 3 (CMIP3) models:

- CCCMA31 (henceforth abbreviated as CCC), developed by the Canadian Centre for Climate Modelling and Analysis
- CSIRO_MK30 (CSIRO), developed by the CSIRO and BoM in Australia
- ECHAM5 (ECHAM), developed by the Max Planck Institute for Meteorology, Hamburg, Germany
- MIROC32 (MIROC), Model for Interdisciplinary Research on Climate, developed in Japan by several institutions.

Each of these was downscaled with three regional models, R1, R2 and R3, based on the Weather Research and Forecasting (WRF) modelling system, as described by Evans et al.

(2014). The global and regional climate models were selected on the basis they could adequately simulate the NARCliM domain climate but could be as independent (i.e. giving different projections) as possible (Evans et al. 2014). The intermediate A2 emission scenario of the Intergovernmental Panel on Climate Change was adopted (IPCC 2000). Each model presents a unique scenario on how annual rainfall and mean annual daily maximum temperatures will change over the following periods:

- the near-future change period: 1990–2009 to 2020–2039
- the far-future change period: 1990–2009 to 2060–2079.

The estimates of climate change over these periods, rather than the absolute values of the two climate variables for each period, are important in this project. Maps presenting the change projected by the mean of all 12 models for the two change periods for both climate variables are shown in Figures 10 to 13. Changes for each of the individual 12 models are presented by Orem et al. (2015). The data used in all these projections had been bias corrected, to more reliably characterise each climate model,

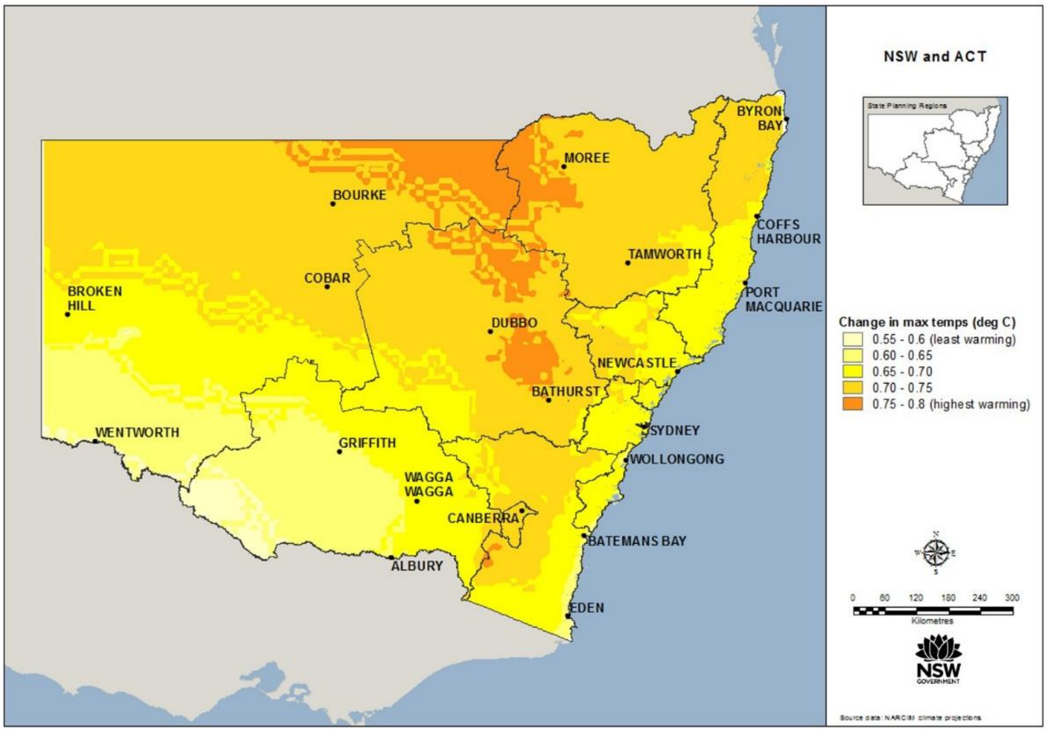

Figure 10 Projected changes in mean daily annual maximum temperatures over New South Wales, near-future change period

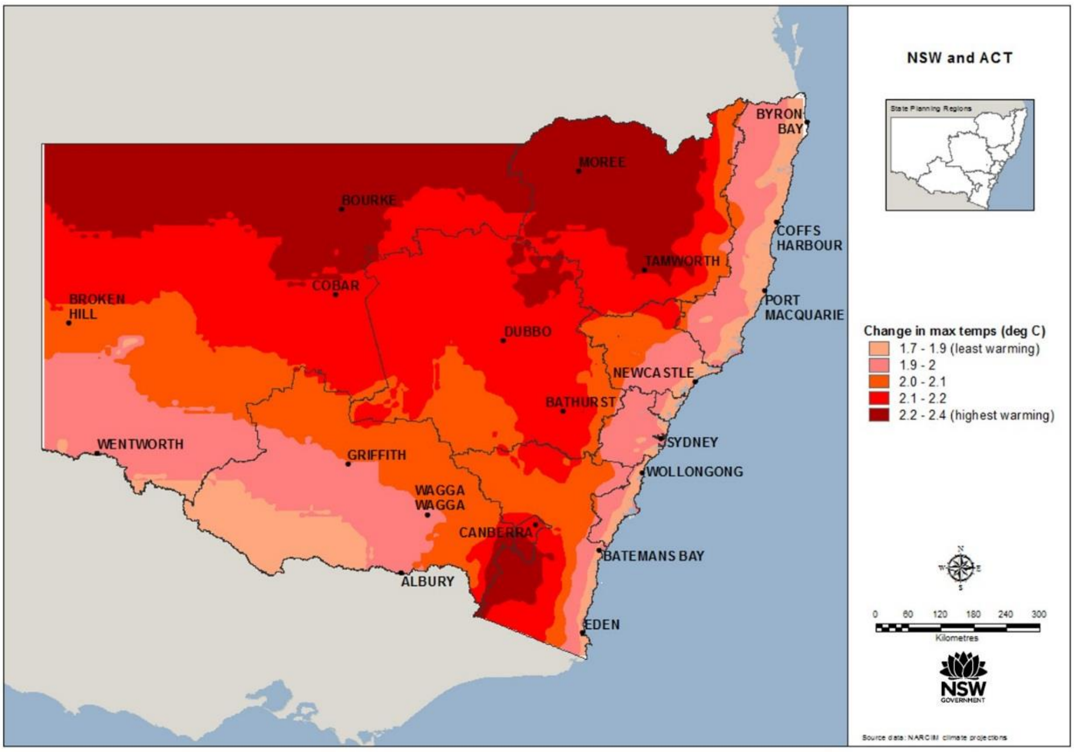

Figure 11 Projected changes in mean daily annual maximum temperatures over New South Wales, far-future change period

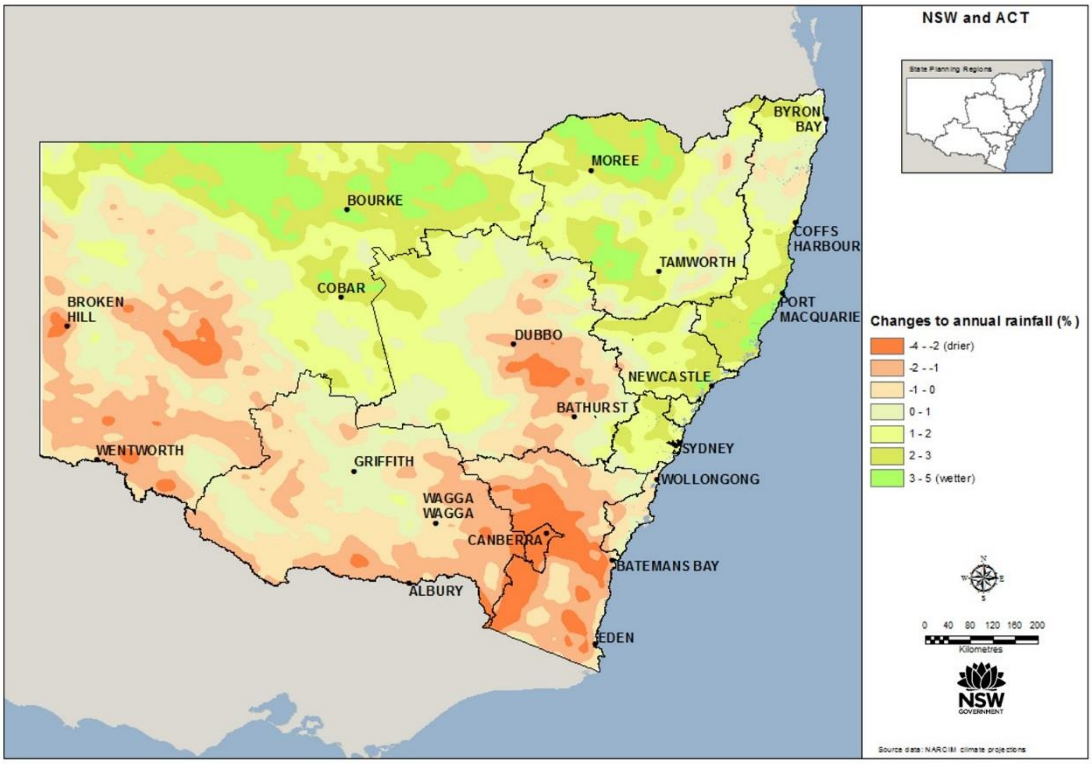

Figure 12 Projected changes in mean annual precipitation over New South Wales, near-future change period

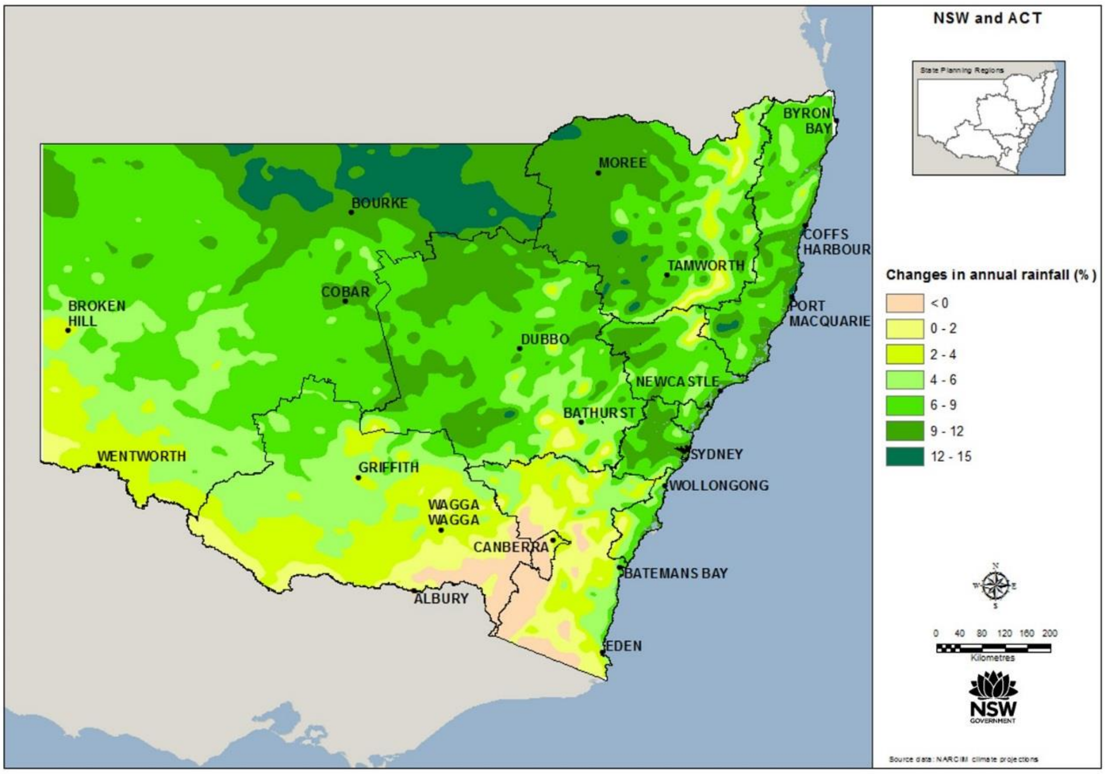

Figure 13 Projected changes in mean annual precipitation over New South Wales, far-future change period

A clear trend of warming conditions over the entire State is seen in Figures 10 and 11, with the most marked increase occurring in the northern part of the State and in the far southern highlands (up to 2.4°C for the far-future change period). Projections presented in the *NSW Climate Change Snapshot* report (OEH 2015) suggest that statewide there will be an approximate 0.4 to 1.0 °C increase in maximum temperatures over the near-future change period and an approximate 1.8 to 2.4 °C increase over the far-future change period.

The average projected trends in annual rainfall across New South Wales (Figures 12 and 13) are more complex. Over the near-future change period there is an apparent slight increase (by 5%) over the northern parts of the state but a slight decrease in the southern parts (down by –4%). Over the far-future change period an increase in annual rainfall over almost the entire State is projected, up to 15% in the far north, but approaching zero in the south. Projections for the State reported by OEH (2015) also demonstrate the variation in different models, with –10% to +11% for the near-future change period and –8% to +20% for the far-future change period.

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4. Results

This section presents the predicted changes in the three soil properties (SOC, pH and sum-of-bases) over New South Wales that will accompany the NARCliM projected climate change. Results are presented over the two broad depth intervals: upper soil (0 to 30cm) and lower soil (30 to 100cm). Primary focus is given to the results for the far-future change period (1990–2009 to 2060–2079), but the raw digital data for the near-future change period is available from the OEH Adapt NSW website.

For each soil property, change is reported:

- on an overall statewide basis
- by physical zone, including broad geographic regions and climate – parent material – land use subclasses
- by State planning region

followed by an overview of the results.

4.1 Organic carbon

State overview

The absolute changes in SOC stocks across New South Wales for the upper (0 to 30cm) and lower (30 to 100cm) depth intervals for the far-future change period are presented in Figures 14 and 15. The changes over these two depth intervals, as derived by using each of the 12 climate models, are presented in the chart of Figure 16.

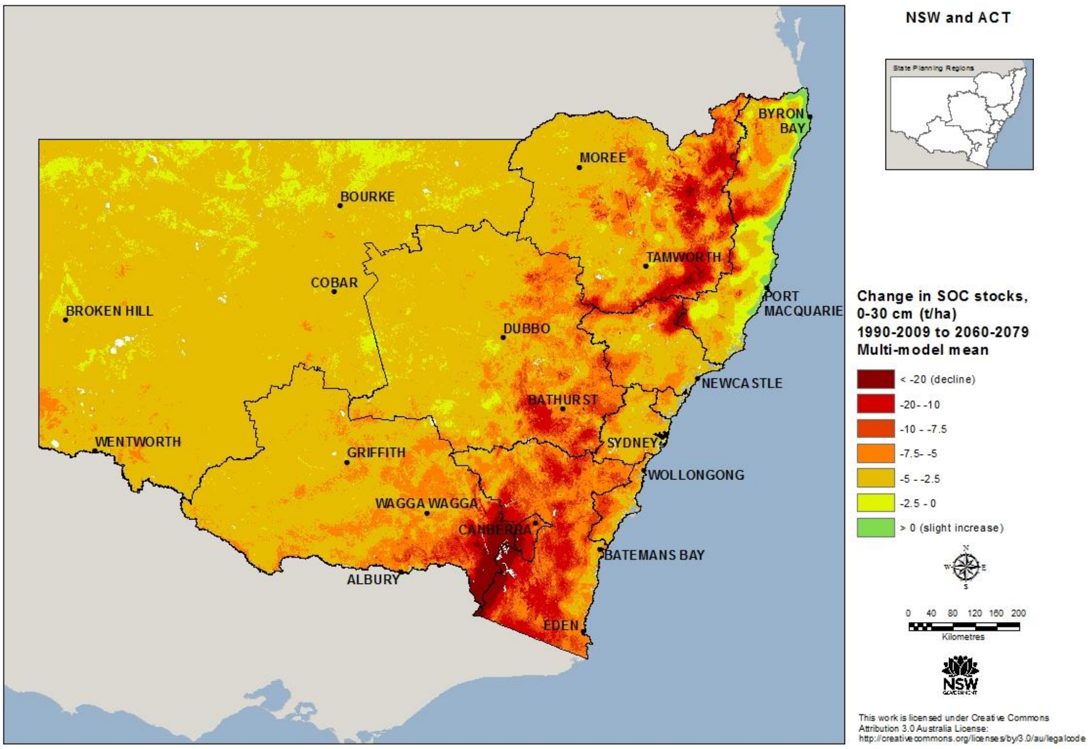


Figure 14 Absolute change in SOC stocks (t/ha) across New South Wales for the far-future change period (0 to 30cm soil depth)

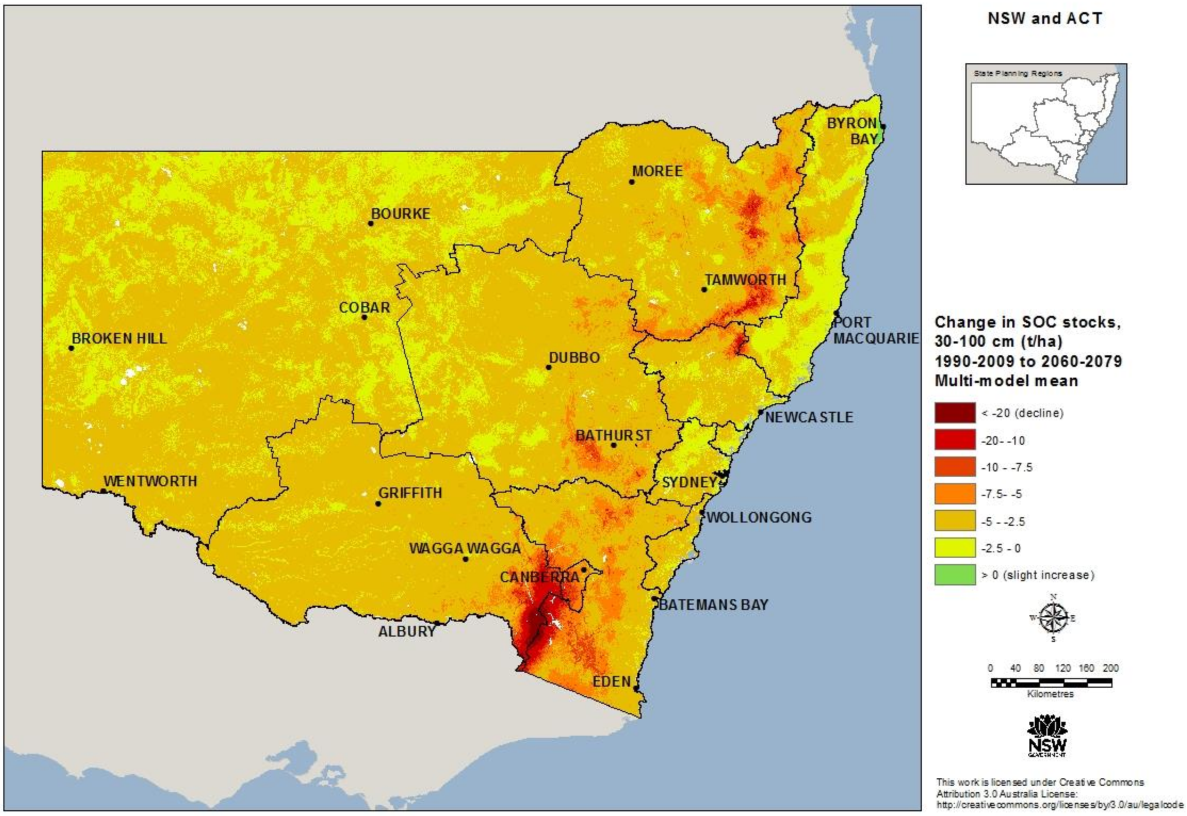


Figure 15 Absolute change in SOC stocks (t/ha) across New South Wales for the far-future change period (30 to 100cm soil depth)

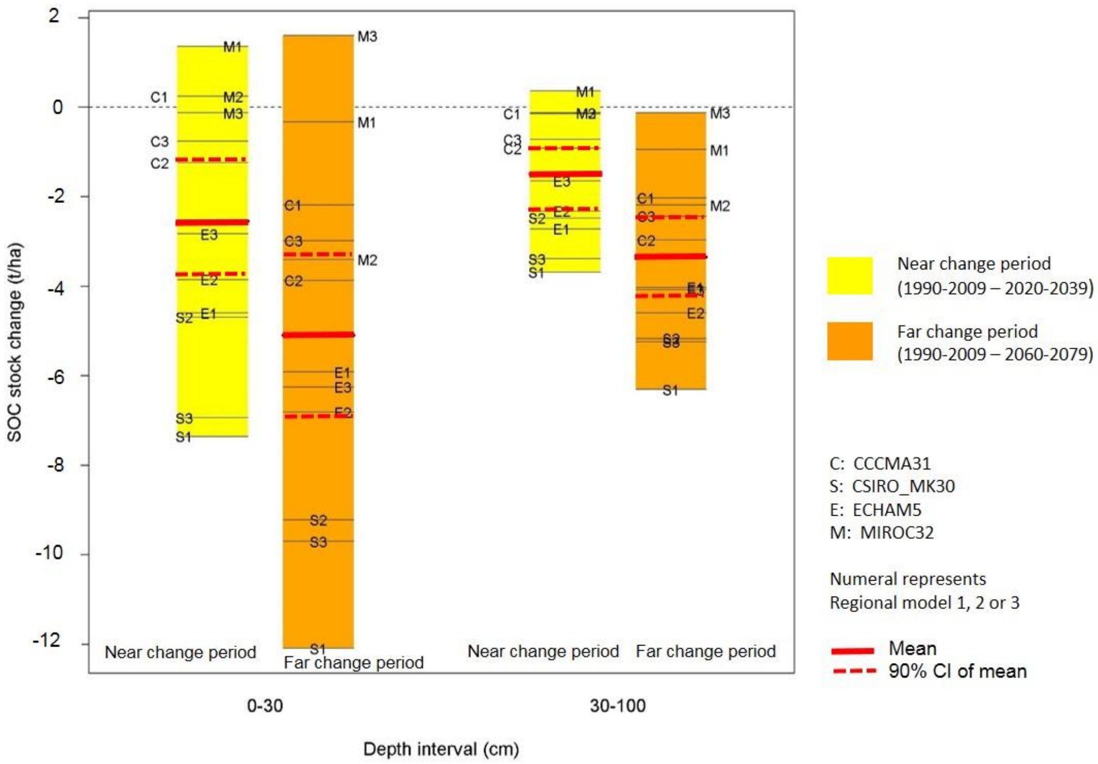


Figure 16 Absolute changes in SOC stocks at two soil depths, obtained from the 12 climate models for both change periods, with 90% confidence intervals

The results suggest an overall decline in SOC stocks across New South Wales, with the extent of change becoming less pronounced at the lower depth interval and more pronounced over the far-future change period. From the average of the 12 models, in the upper depth interval (0 to 30cm), there is a statewide average 2.5t/ha decrease to the near-future change period and 5.1t/ha to the far-future change period (Figure 16). There are only slight overall declines in the lower depth intervals (30 to 100cm), of only 1.5t/ha (near-future) and 3.3t/ha (far-future).

The extent of the SOC decline, however, varies significantly with the different climate models. The least decline is predicted by the more moist MIROC and CCC models, which in some cases reveal a slight statewide increase up to 1.6t/ha. By contrast, the CSIRO models, which project drier conditions, suggest substantial decreases of over 12t/ha for the CSIRO R1 model for the upper depth interval in the far-future change period. The ECHAM models all reveal a greater than average decrease in SOC stocks.

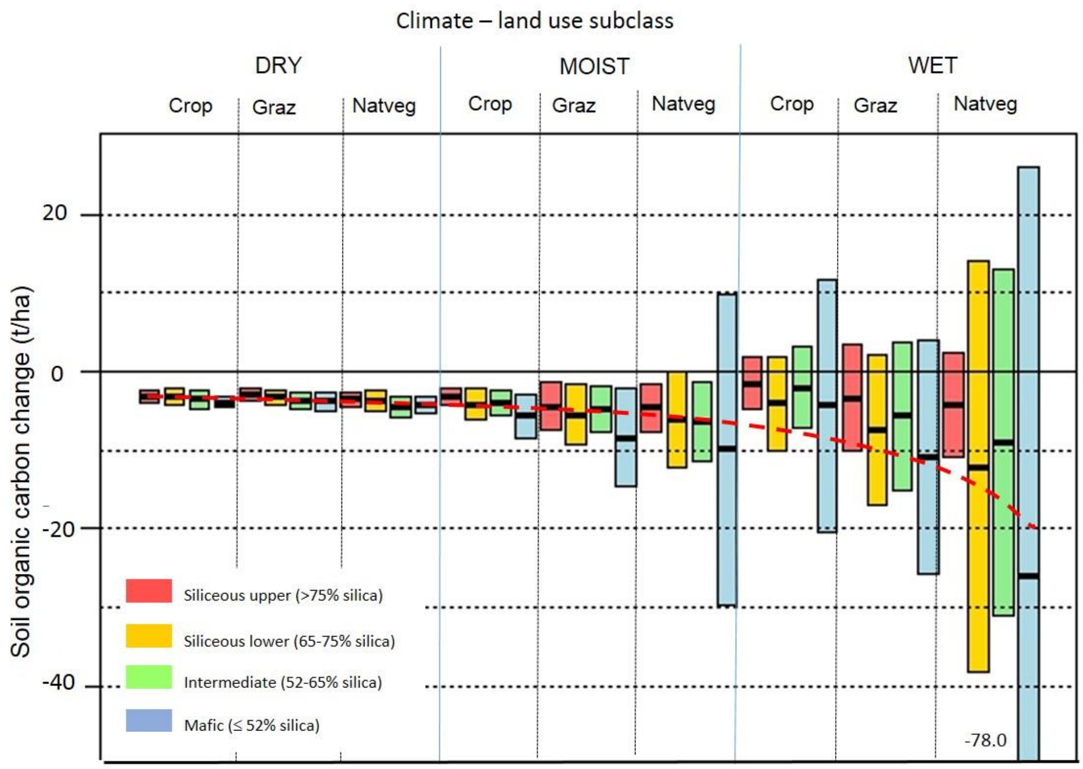
Physical zones

The maps of SOC stock changes over New South Wales for the far-future change period (Figures 14 and 15) reveal that, based on the average of all climate models, most of the State is projected to undergo a modest decrease in SOC stocks (0 to 7.5t/ha in the upper depth, 3 to 5t/ha in the lower depth). Projected losses are greater in the highland areas, exceeding 20t/ha (for upper depth) in the far southern alpine regions. Minor areas along the far north coast, however, have projected slight increase in stocks (generally less than 2t/ha).

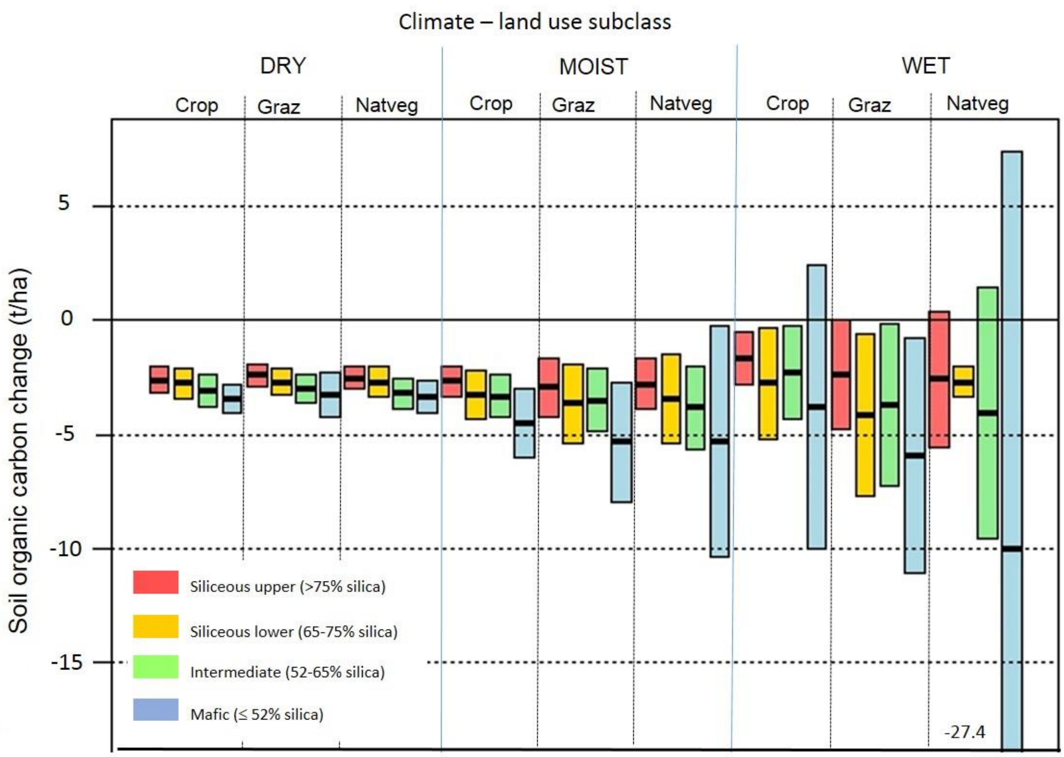
The SOC changes demonstrated over any region by the maps depend primarily on the balance between the changing temperatures and rainfall over that region. SOC generally decreases with rising temperatures and decreasing rainfall (Jenny 1980; Badgery et al. 2013; Hobley et al. 2015). For example, the ACT/far southern highlands region shows a substantial decrease in SOC, reflecting the average projected lower rainfall (Figure 13) and hotter temperatures (Figure 11). In contrast, parts of the North Coast Region show only a minor decrease in SOC, reflecting the slight increase in rainfall, and relatively lower rise in temperatures.

However, the extent of the SOC change also varies with the environmental and land use regime, and this adds complexity to the above trends. Figure 17 presents a breakdown of the SOC changes for the upper (0 to 30cm) and lower (30 to 100cm) depth intervals over the far-future change period by current climate – parent material – land use subclasses. Vertical bars represent the upper and lower 90% confidence intervals; the mean derived from the 12 climate models for each subclass is also shown. Only when the bar does not intersect the zero change line can we be confident (at the 90% level) of a change based on the 12 climate models.

The plots reveal that the extent of SOC stock change varies among different current climate – parent material – land use regimes. For example, in the upper (0 to 30cm) interval, a mean loss of 26.0t/ha is projected for the moist – mafic parent material – native vegetation regime, whereas only 3.1t/ha loss is projected for the dry – upper siliceous – cropland regime. The broad trend is indicated by the dashed line on the 0 to 30cm plot.



0 to 30cm soil depth



30 to 100cm soil depth

Figure 17 Mean changes and 90% spread of predictions in SOC stocks, by physical zone, from the 12 NARCliM models (t/ha, 0 to 30cm and 30 to 100cm soil depth, far-future change period)

Graz: grazing; Natveg: native vegetation; dashed line indicates trend of change

Although there are some anomalies over both depth intervals, they both present a trend of increasing loss of SOC stocks with increasingly moist current conditions, more mafic parent material and less intensive land uses. The 90% spread of predictions also increases with the same trends.

These trends suggest the extent of absolute change in SOC with the projected climate change depends broadly on the initial levels in the soil. Soils with inherently high SOC levels will lose or gain more SOC than those with inherently low SOC levels. We recently demonstrated the inherently higher SOC storage levels of soils under moist, mafic (high-fertility) parent material and high vegetation cover regimes across eastern Australia (Gray et al. 2015a).

State planning regions

The overall changes in SOC stocks within the upper and lower depth intervals over both change periods for the 11 State planning regions of New South Wales (including the ACT) and the State as a whole, are shown by the plot in Figure 18. The SOC-change maps in Figures 14 and 15 (see Figure 2 for the identification of State planning regions) provide further details on the SOC stock changes in each region.

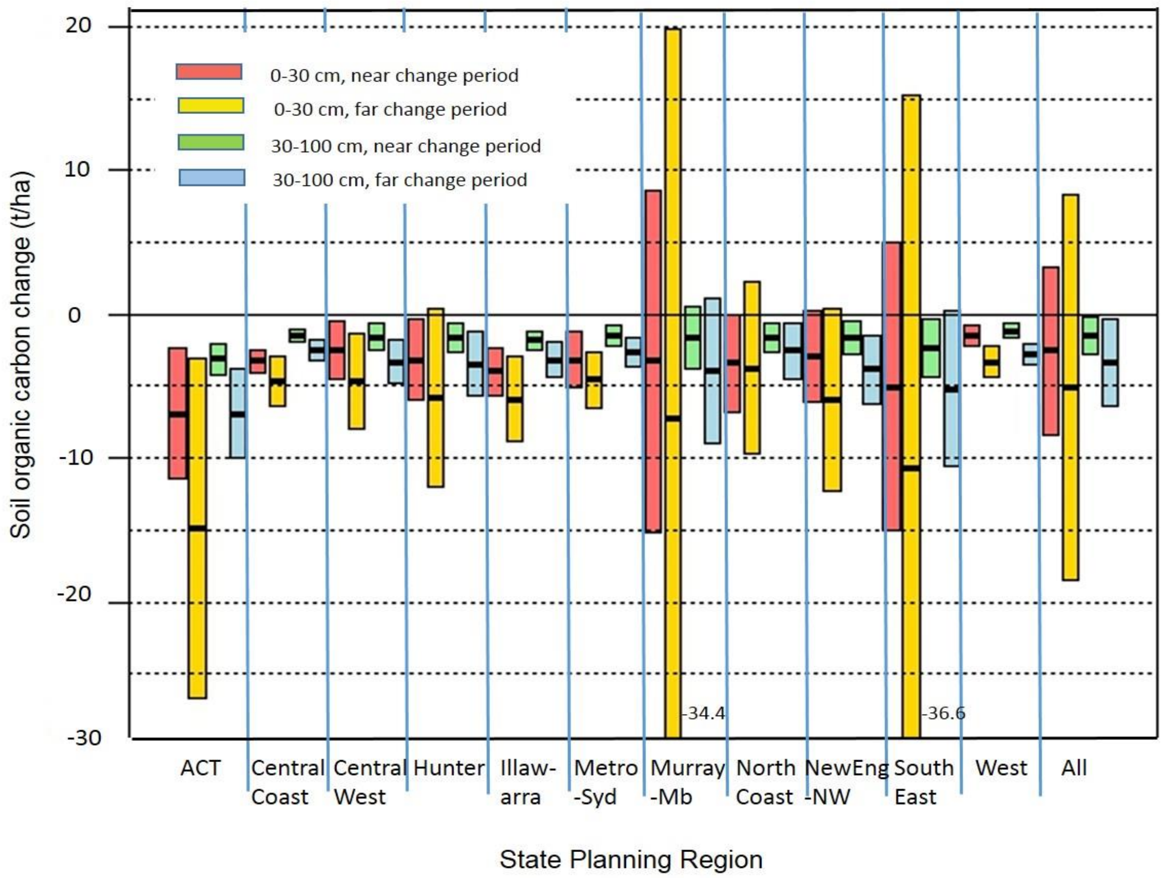


Figure 18 Mean changes and 90% spread of values, by State planning region over both change periods (0 to 30cm and 30 to 100cm soil depth; t/ha)

The results in Figure 18 broadly reflect the regional changes described in the previous sections. Bearing in mind the variations in predictions from the different climate models, the highest levels of mean absolute decline and spread of predictions are predicted for the cool-moist ACT and South East and Tablelands regions (up to 14.9 and 10.7t/ha decline respectively) and the least decline in the dry Far West Region (only 3.3t/ha decline in the upper depth, far-future change period). In most regions, the extent of SOC stock change is more marked over the far-future change period than for the near-future change period.

These results reflect the differing projected changes in climate and the different environments that dominate each of these State planning regions, with those containing high proportions of moist climates, intermediate or mafic materials and undisturbed vegetated lands undergoing the greatest change in SOC. The trends revealed are somewhat dampened because of several State planning regions being spread over broad regions with wide ranges of climatic and other environmental conditions.

Discussion

An average overall slight to moderate decline in SOC stocks is predicted over most of the State using the average projected climate changes from the NARCliM models, although a slight increase is predicted over some regions – particularly the more western regions.

A wide variation in predicted SOC changes is apparent, depending on the climate model used. As SOC stocks normally decline with increasing temperatures and decreasing rainfall, the models that present the greatest warming and drying trends, such as the CSIRO models, are associated with the most notable statewide declines in SOC. By contrast, the models presenting wetter trends, such as the MIROC and CCC models, all tend to predict only slight decreases in SOC. With the advent of more accurate and reliable climate change models, greater confidence in the predicted trends in SOC levels across the State should be possible.

The predicted changes in SOC have implications for the health of NSW soils. Lower SOC contents are associated with a decline in soil health owing to the multiple benefits associated with organic material, including improved nutrient supply, soil structure, aeration and water-holding capacity (McKenzie & Dixon 2006; Baldock et al. 2012; Murphy 2015). For those regions identified as undergoing SOC declines, a decline in agricultural productivity may occur unless remediating measures are undertaken. For those regions where slight increases are projected, agricultural productivity may benefit.

The results also have implications for climate change mitigation programs that are based upon increased soil carbon sequestration. Our results suggest that baseline soil carbon storage will significantly decline over most of the State; this means that even greater enhanced management by landholders will be needed to produce the desired soil carbon increases.

4.2 pH

State overview

The average projected change in pH across New South Wales for the upper (0 to 30cm) and lower (30 to 100cm) depth intervals for the far-future change period are presented in Figures 19 and 20. The changes over these two depth intervals, as derived by using each of the 12 climate models, are presented in the chart of Figure 21.

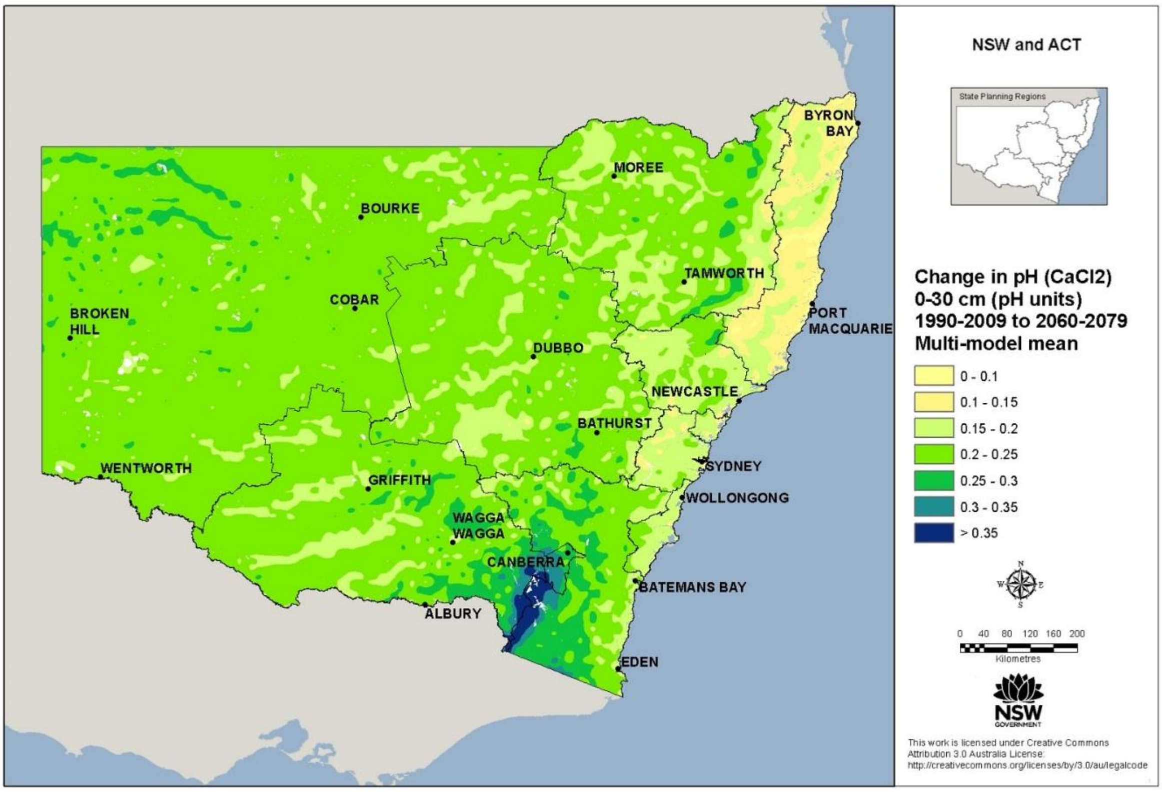


Figure 19 Absolute changes in pH across New South Wales for the far-future change period (0 to 30cm soil depth)

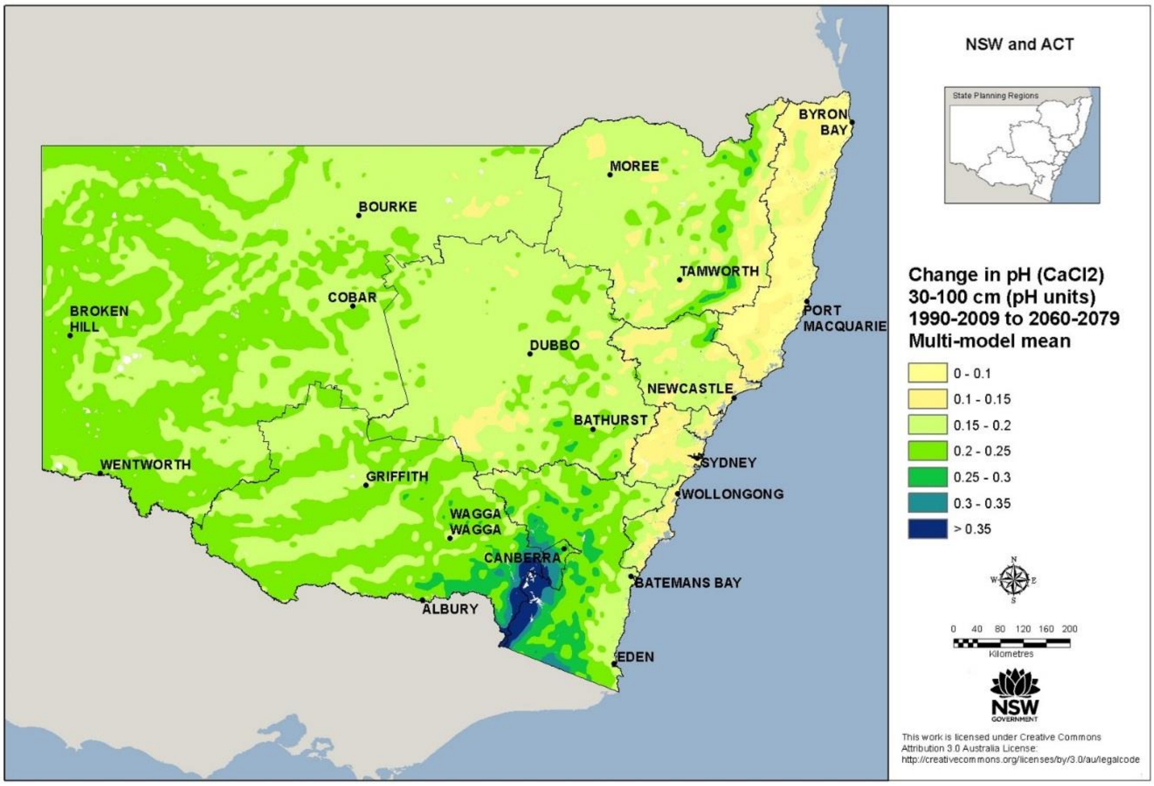


Figure 20 Absolute changes in pH across New South Wales for the far-future change period (30 to 100cm soil depth)

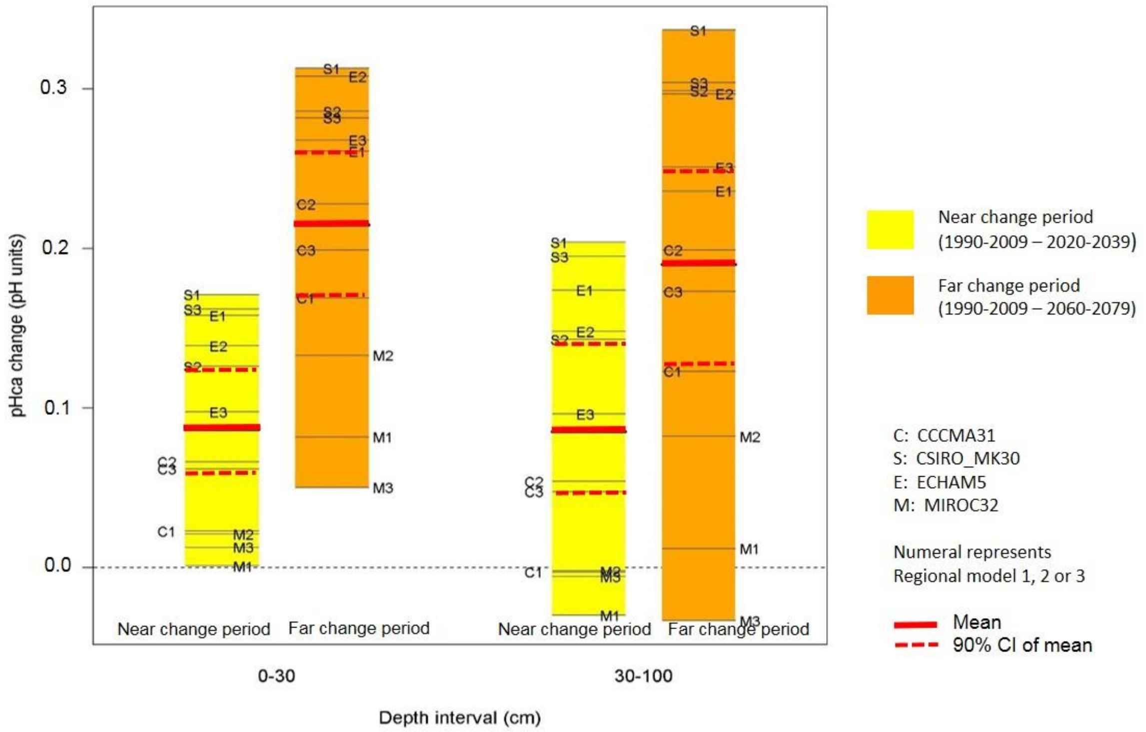


Figure 21 Absolute changes in pH at two soil depths, obtained from the 12 climate models for both change periods with 90% confidence intervals

The results suggest that from the average of all 12 climate models, there is a minor increase in pH levels across the State, i.e. a trend towards alkalinity. The increases are highest over the far-future change period, and slightly higher for the upper depth interval, with statewide averages of approximately 0.22 and 0.19 pH units for both the upper and lower intervals respectively (Figure 21).

The extent of pH increase, however, varies significantly with the different climate models. The CSIRO and ECHAM models, which project relatively drier conditions, suggest notable increases over 0.3 pH units over the far-future change period (Figure 21). By contrast, the MIROC and CCC models, which project more moist conditions, predict only slight increases, or even fractional decreases (of 0.03 units) for the lower depth interval for some of the MIROC models.

The influence of possible ongoing acidification over agricultural lands resulting from intensive agricultural practices was not included in this analysis, as elaborated on in the Discussion section below.

Physical zones

Figures 19 and 20 demonstrate that, based on the average from all 12 models, pH increases are the lowest in the north-east of the State generally rising towards the west and to the south. The highest increases of over 0.35 pH units are predicted in the far southern alpine regions.

The pH change demonstrated over any region by the maps is primarily controlled by the balance between the changing temperatures and rainfall over that region. Soil pH normally increases with rising temperature and declining rainfall (Gray et al. 2015b; Rubinic et al. 2015). The widespread increase in pH across the State with the projected climate change is attributable to the rising temperatures (projected by all models) which outweigh the overall slight increase in rainfall (average of all models, see Figures 10 to 13). The marked increase in pH around the far southern highlands reflects the combination of highly warming conditions and average slight decrease in rainfall.

The extent of the pH change may also vary with the environmental and land use regime, adding complexity to the above trends. Figure 22 presents a breakdown of the pH change results for the upper and lower depth intervals over the far-future change period by climate – parent material - land use subclass. Vertical bars represent the upper and lower 90% spread of predictions; also shown are means derived from the 12 climate models for each subclass. There are, however, no clear trends in the mean change values. The increase appears to be greatest (approximately 0.22 for upper depth, far-future change period) for currently dry climates and least for currently wet climates (approximately 0.17 for the equivalent depth-change period). The 90% spread of predictions is certainly greatest for the currently wet environments.

State planning regions

The overall changes in pH within the upper and lower depth intervals over the two change periods for the 11 State planning regions of New South Wales (including the ACT) and the State are shown by the plots in Figure 23. The pH change maps in Figures 19 and 20 provide further detail on pH changes by State planning region.

The results in Figure 23 broadly reflect the regional changes described in the previous sections. Despite the variation in predictions from the different climate models, the results suggest overall slight increases in pH over almost all State planning regions, generally between 0.15 to 0.25 pH units for the far-future change period, at both depth intervals.

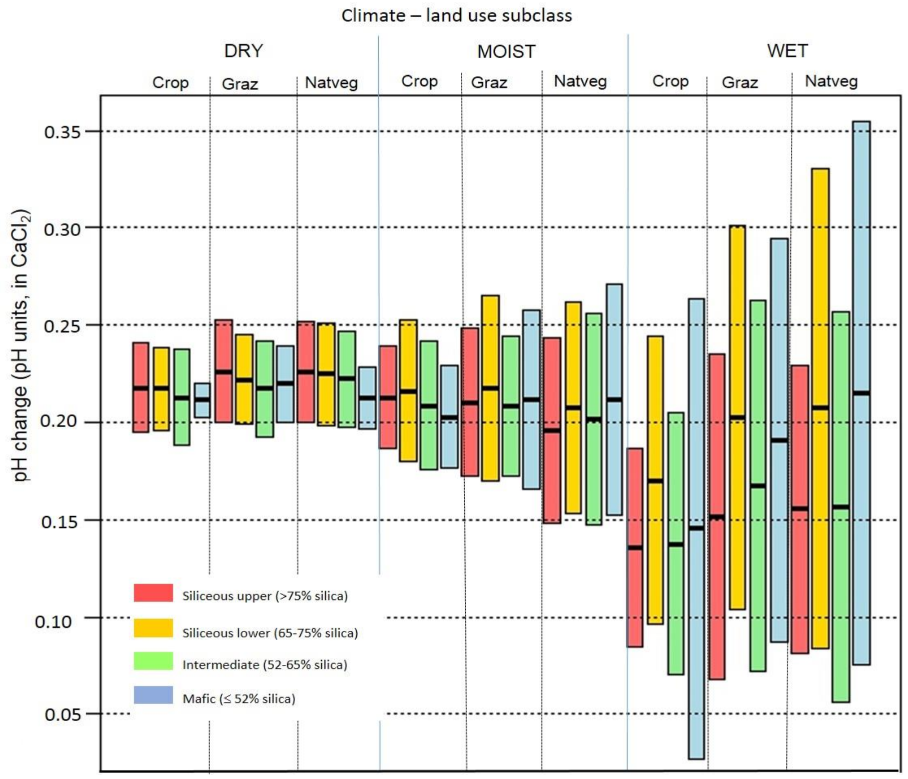
The highest levels of mean absolute increase and spread of predictions are predicted for the ACT and South East and Tablelands regions (up to 0.3 and 0.25 pH unit increase respectively for the upper depth, far-future change period), with the Murray–Murrumbidgee and western regions also expected to undergo higher than average pH increases. The least decline is predicted for the North Coast region (only 0.14 pH unit increase in the upper depth, far-future change period). In most regions, the extent of pH increase is more marked over the far-future change period than for the near-future change period.

Discussion

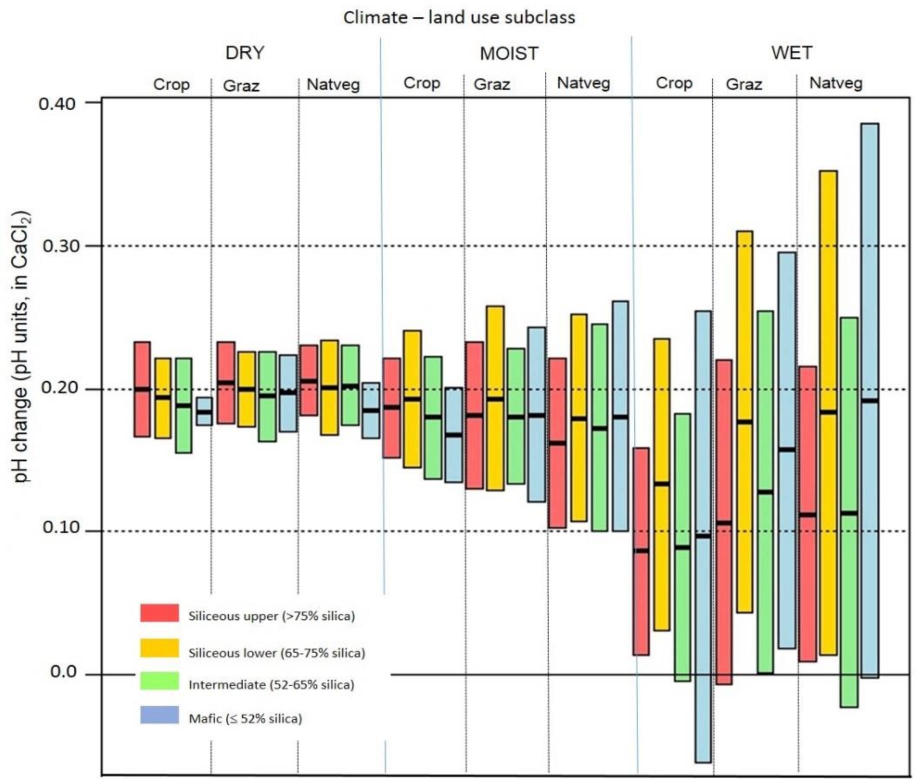
The results from the averages of the 12 climate change models indicate a minor increase in pH over most of the State, i.e. a trend towards alkalinity. The far southern highlands and the far western regions are predicted to undergo the greatest pH increases.

A wide variation in the extent of pH increase is apparent, depending on the climate model used. pH levels normally rise with increasing temperatures and decreasing rainfall Gray et al. 2015b; Kopittke et al. 2012; Webb et al 1986). This results from the lower levels of leaching that allows basic cations to be retained in the soil and not replaced by hydrogen and aluminium ions (McKenzie et al. 2004). This means the climate models that present the greatest warming and drying trends, such as the CSIRO models, are associated with the most notable statewide increases in pH. By contrast, the models presenting wetter trends, such as the MIROC and CCC models, all tend to reveal smaller increases in pH. The advent of more accurate and reliable climate change models will allow greater confidence in the predicted trends for pH across the State.

Over most of the State the changes in pH are quite small and are not likely to significantly affect agricultural practices, but they may still need to be considered by farm managers, especially when a crop or pasture species requires a narrow pH range (Hazelton & Murphy 2007).



0 to 30cm soil depth



30 to 100cm soil depth

Figure 22 Mean changes and 90% spread of predictions of pH by physical zone from the 12 NARCliM models (pH units, 0 to 30cm and 30 to 100cm soil depth, far-future change period)

Graz: grazing; Natveg: native vegetation

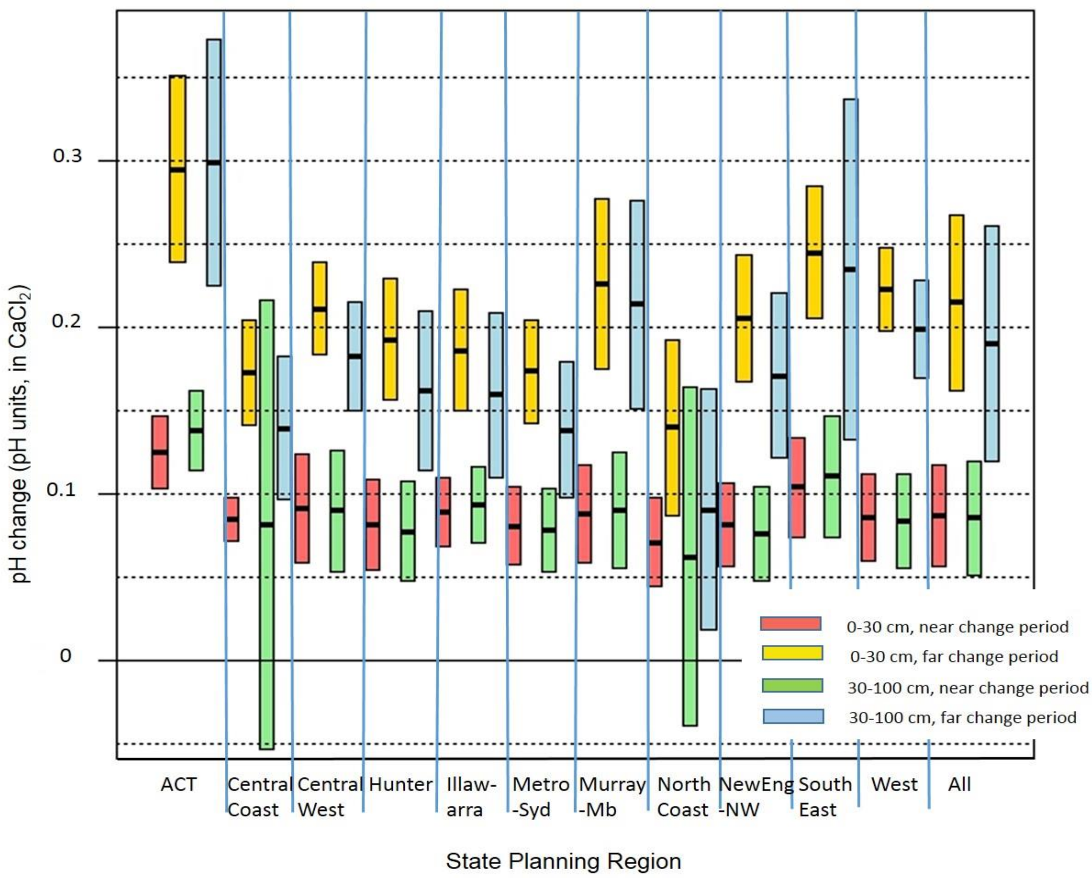


Figure 23 **Mean pH change and 90% spread of values by State planning region over both change periods (0 to 30cm and 30 to 100cm soil depth)**

The modelling process applied in this study did not include effects of ongoing or evolving land management. In agricultural lands, there may be continuing acidification due to effects of leaching, application of nitrogenous fertilisers and biomass removal (Fenton and Helyar 2007). Although a broad trend towards alkalinity was revealed by considering climate change alone, the agricultural trends towards acidification may override the purely climatic effects. The projected results presented in this study are best interpreted as the change due to climate change only, i.e., ongoing land management impacts are not considered. For example, ongoing intensive agriculture over a particular location to 2070 may lead to a decline in pH of 0.2 units, but the effect of climate change (as presented in current results) may be for an 0.1 pH unit rise, meaning the overall change may still be an 0.1 decline in pH.

Any changes in soil pH may affect natural ecosystems, which have normally become established under particular pH ranges. Where significant increases or decreases (e.g. of 0.25 pH units or more) are demonstrated there is a likelihood that native ecosystems will be affected; this is an issue that may need to be considered and addressed by managers of these ecosystems.

4.3 Sum-of-bases

State overview

The relative changes in the sum-of-bases (a subset of macro-nutrients) across New South Wales over both depth intervals (0 to 30cm and 30 to 100cm) for the far-future change period are presented in Figures 24 and 25. The changes over these two depth intervals, as derived by using each of the 12 climate models, are presented in the chart of Figure 26.

The results from the averages of the 12 models suggest an overall relative increase in the sum-of-bases across the State. This is particularly evident over the far-future change period, in which there is a mean increase of 14.6% in the upper depth interval and 17.4% in the lower depth interval. The changes are generally slightly more pronounced in the lower depth interval.

Predictions of the extent of increase vary significantly, however, among the different climate models. The relatively 'dry' CSIRO and ECHAM models reveal the greatest levels of increase in the sum-of-bases, with CSIRO R1 displaying a 29.7% increase over the lower depth interval in the far-future change period, whereas the relatively 'wet' MIROC and CCC models display the least increases, with MIROC R1 actually displaying a minor decrease of 1.3% over the lower depth interval in the near-future change period.

The influence of possible ongoing nutrient application/depletion over agricultural lands resulting from agricultural practices was not included in this analysis, as elaborated on in the Discussion section below

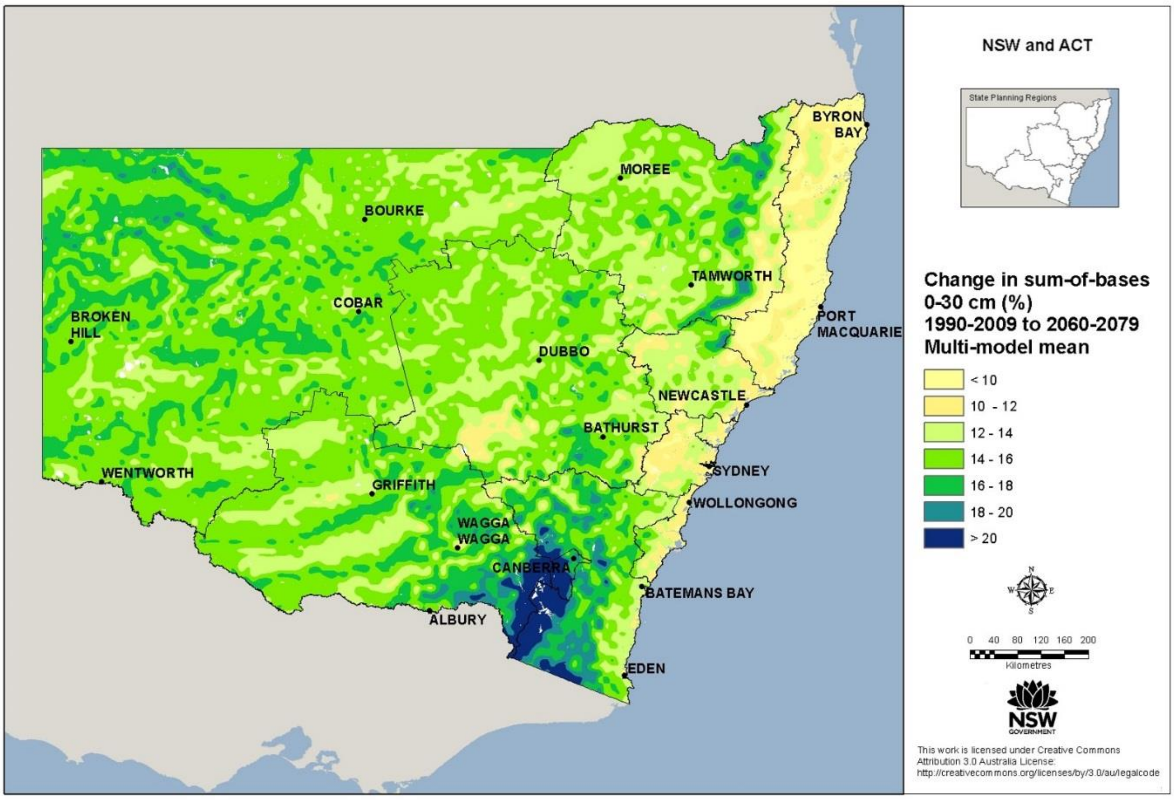


Figure 24 Relative changes in the sum-of-bases across New South Wales for the far-future change period (0 to 30cm soil depth)

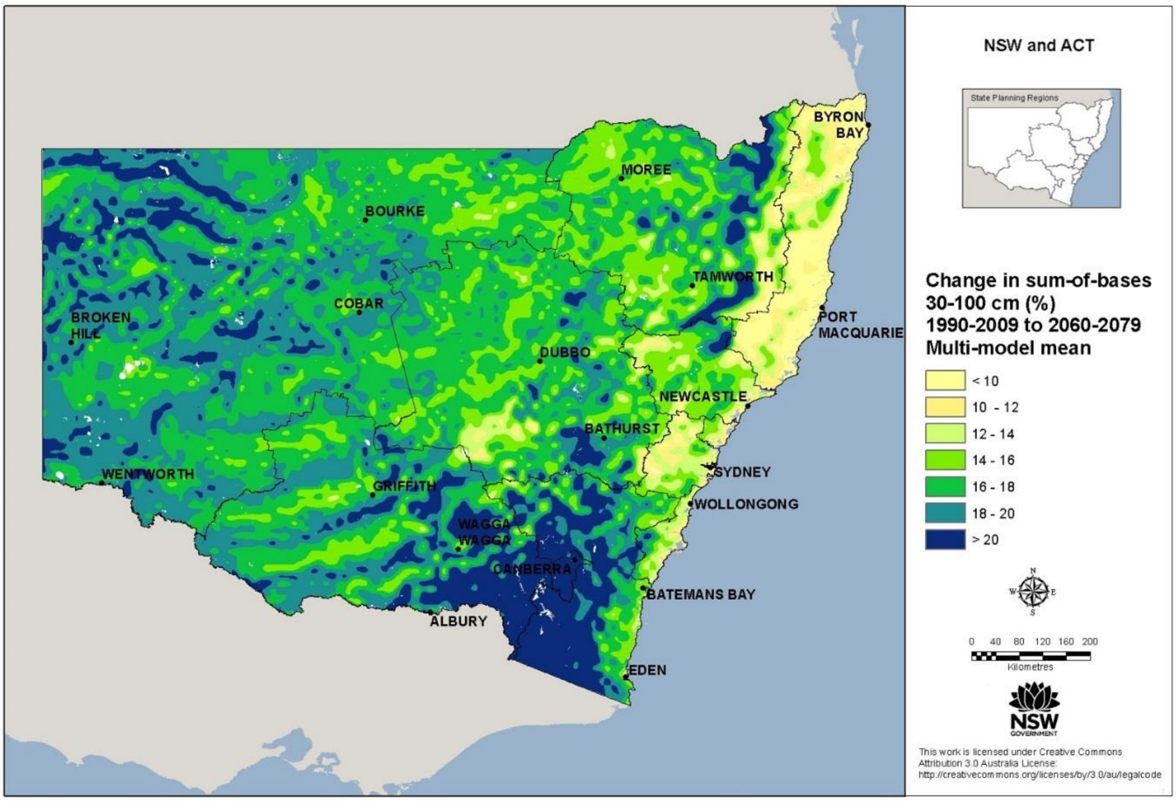


Figure 25 Relative changes in the sum-of-bases across New South Wales for the far-future change period (30 to 100cm soil depth)

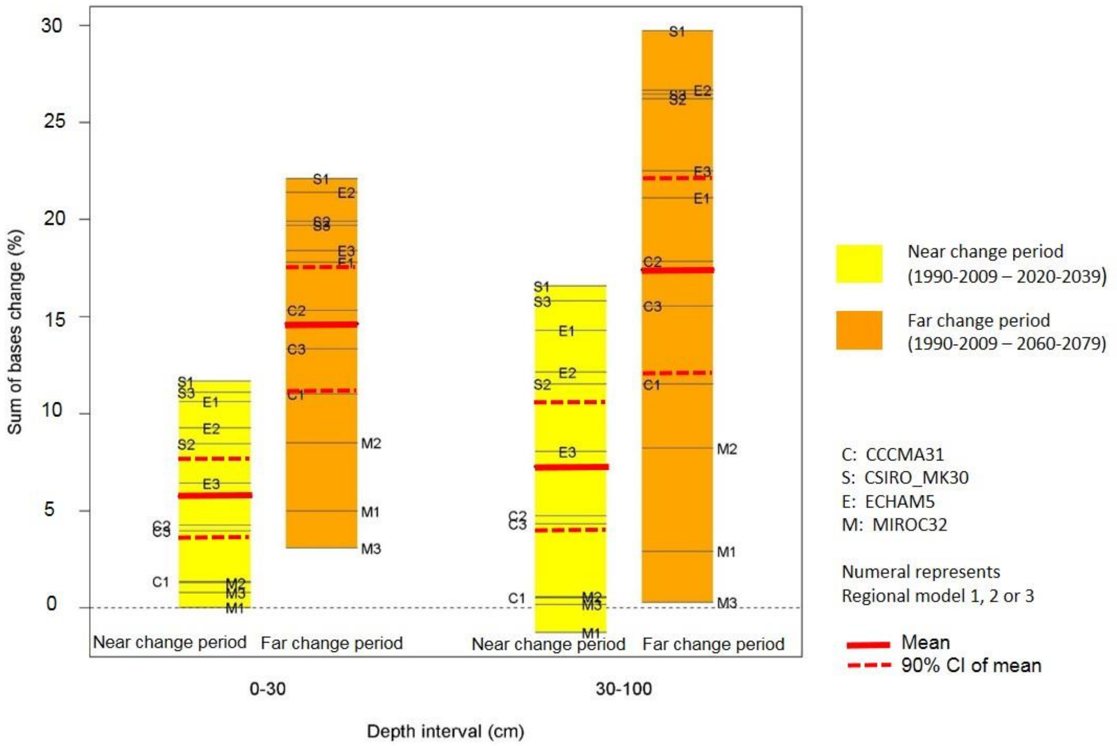


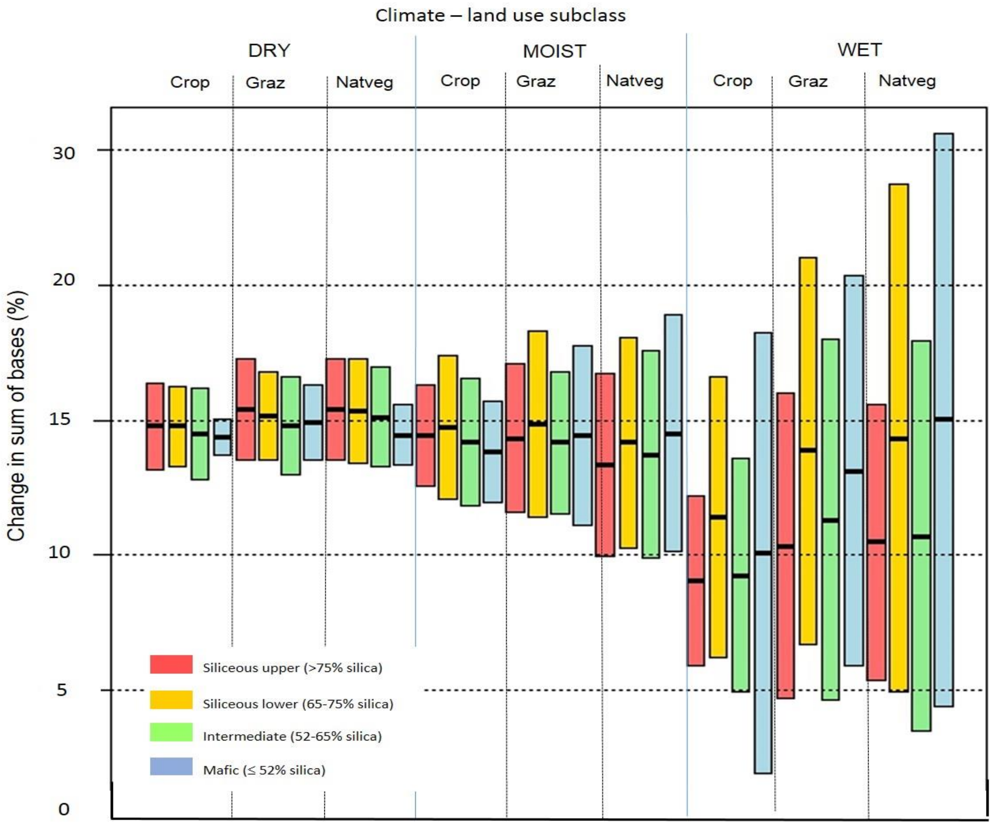
Figure 26 Relative changes in the sum-of-bases at two soil depths, obtained from the 12 climate models for both change periods with 90% confidence intervals

Physical zones

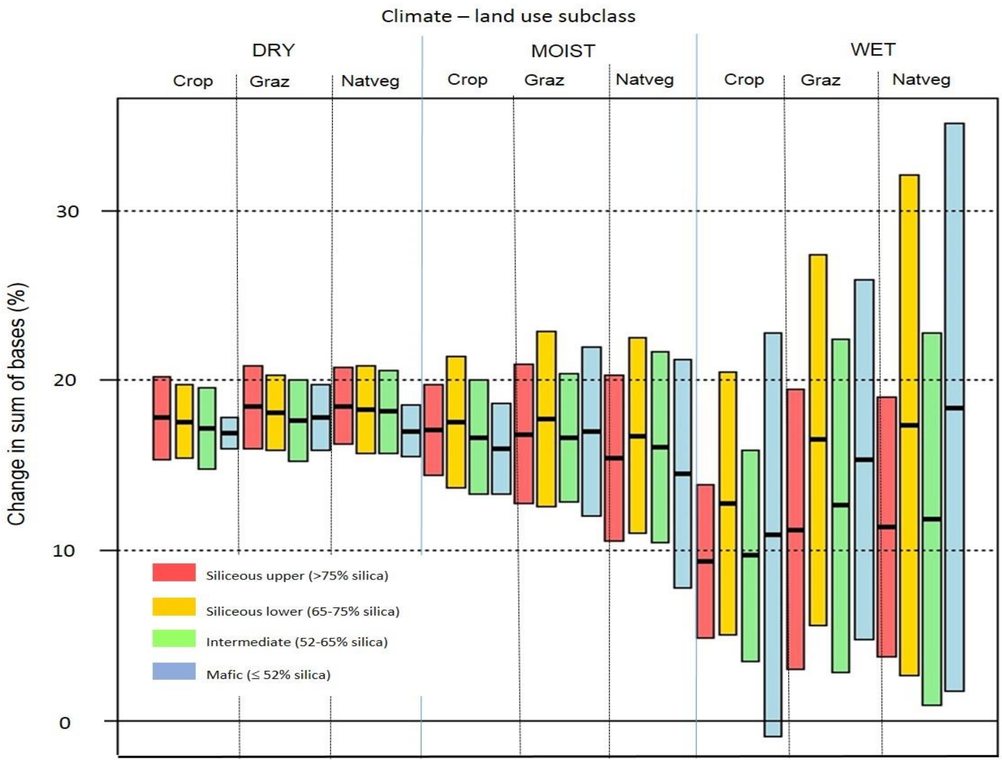
The maps in Figures 24 and 25 reveal that most of the State is projected to undergo a moderate relative increase in the sum-of-bases (typically in the order of 10–20% or more) over both depth intervals in the far-future change period. Highland regions, particularly in the far south of the State, are projected to undergo the greatest increases (over 20%) while the central and northern coastal regions are projected to undergo the least increases (less than 10%).

The change in the sum-of-bases demonstrated over any region by the maps is primarily controlled by the balance between changing temperatures and rainfall over that region, which influence the extent of weathering and leaching processes. The sum-of-bases is typically positively correlated with rising temperatures and negatively correlated with rainfall, reflecting the lower levels of leaching associated with drier conditions, meaning basic cations are retained in the soil structure (McKenzie et al. 2004; Gray et al. 2015b; Rubinic et al. 2015). Thus, the widespread increase predicted over most of the State is a consequence of warmer conditions which outweigh the projected increases in rainfall, particularly over the far-future change period (see Figure 13).

The extent of the change may also vary with the environmental and land use regime, adding complexity to the above trends. Figure 27 presents a breakdown of the sum-of-bases change results for the upper and lower depth intervals over the far-future change period by climate – parent material – land use subclass. Vertical bars represent the upper and lower 90% spread of predictions; also shown are means derived from the 12 climate models for each subclass. There are, however, no clear trends in the mean change values. The increase appears to be greatest for currently dry climates (approximately 15% for upper depth, far-future change period) and least for currently wet climates (approximately 12% for the equivalent depth-change period), but there is variability in these changes. The 90% spread of predictions is clearly the greatest for the currently wet environments.



0 to 30cm soil depth



30 to 100cm soil depth

Figure 27 Mean changes and 90% spread of predictions in sum-of-bases, by physical zone, from the 12 NARCliM models (percentage change, 0 to 30cm and 30 to 100cm soil depth, far-future change period)

Graz: grazing; Natveg: native vegetation

State planning regions

In addition to the maps of Figures 24 and 25, the overall changes in the sum-of-bases (macro-nutrients) over both depth intervals and change periods for the 11 State planning regions of New South Wales (including the ACT) are shown by the chart of Figure 28.

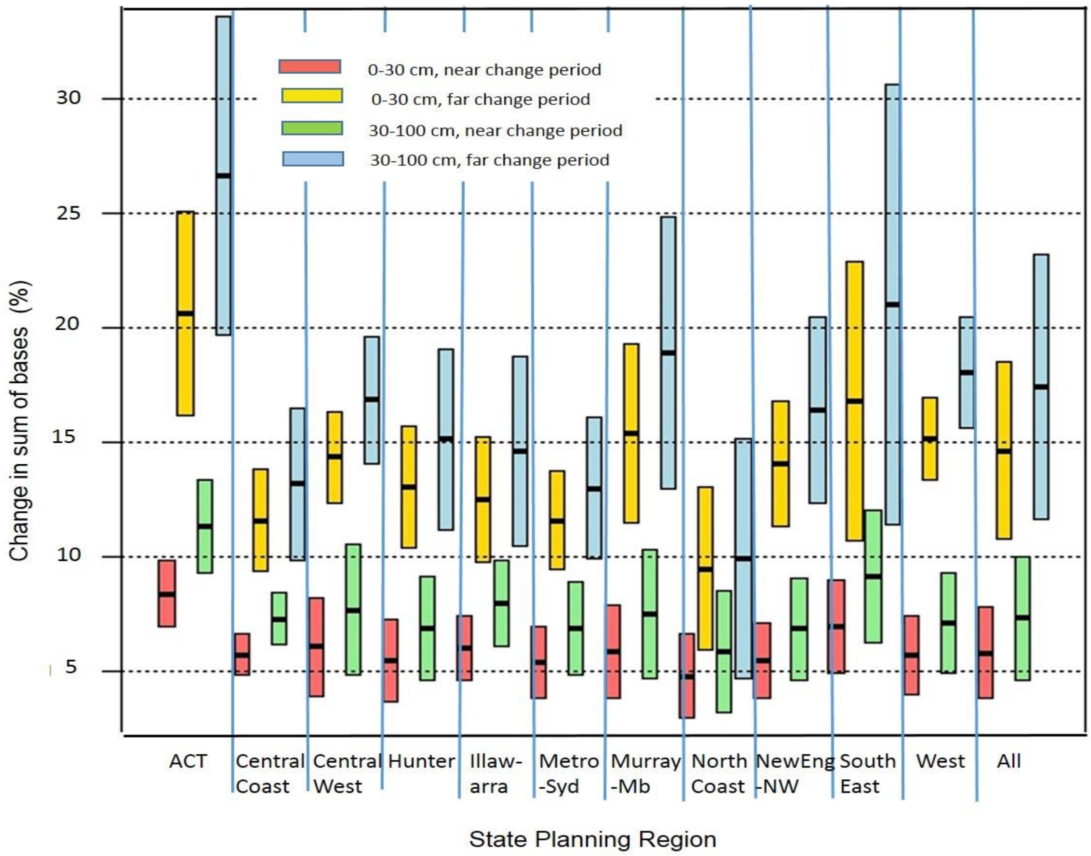


Figure 28 Mean relative change in sum-of-bases and 90% spread of values by State planning region over both future change periods (0 to 30cm and 30 to 100cm soil depth, %)

If the change in sum-of-bases was presented in absolute terms (i.e. in $cmol_c$/kg) rather than the relative terms (i.e. %) then the highest changes would be demonstrated for dry, mafic conditions, which typically have the highest absolute levels of bases.

As was the case for pH, the extent of change over most environmental regimes was more marked over the far-future change period than for the near-future change period. The magnitude of the changes and the widths of the confidence intervals tend to be slightly greater in the lower soil depth interval.

The results demonstrated in Figure 28 broadly reflect the regional changes described in the previous sections. Despite the variation in predictions from the different climate models, the results suggest overall moderate increases in sum-of-bases over all State planning regions, generally between 10 to 20% for the far-future change period, at both depth intervals. They parallel results presented for pH.

The highest levels of relative increase and spread of predictions are revealed for the ACT and South East and Tablelands regions (up to 27% and 21% increase respectively for the lower depth, far-future change period), with the Murray–Murrumbidgee and western regions also expected to undergo higher than average increases. The least decline is predicted for the North Coast Region (only 10% increase in the lower depth, far-future change period). In most regions, the extent of sum-of-bases increase is more marked over the far-future change period than for the near-future change period and in the lower depth interval.

Discussion

The results from the averages of the 12 climate change models indicate a moderate increase in sum-of-bases (common macro-nutrients) over most of the State. The far southern highlands and the far western regions are predicted to undergo the greatest increases.

The climate models used in this study give rise to wide variations in the extent of predicted increase in macro-nutrient across New South Wales. As for pH, macro-nutrient levels normally rise with increasing temperatures and decreasing rainfall, meaning that the climate models that present the greatest warming and drying trends, such as the CSIRO models, are associated with the most notable statewide increases in this soil property. By contrast, the models presenting more moist trends, such as the MIROC and CCC models, tend to reveal lesser increases in this soil property. Again, more accurate and reliable climate change models will provide greater confidence in predictions of macro-nutrient levels across the State.

Changes in the levels of macro-nutrients influence soil fertility and agricultural productivity (McKenzie et al. 2004). Such changes may also indicate similar changes in many important minor and trace nutrients, and this may be a cause for concern if crop or pasture species have narrow tolerance ranges (Mulvey & Elliott 2007). The predicted modest rise in this suite of macro-nutrient levels over most of the State should generally benefit agricultural productivity, except if the rise comes from sodium, which can have deleterious effects on the soil (Hazelton & Murphy 2007).

Nutrient addition or removal due to agriculture (Charman 2007) were not directly considered in our DSM process. These changes may be more significant than the effects of climate change alone, as was discussed for pH and ongoing agricultural driven acidification. Thus, if nutrient decline over an intensive agricultural operation to 2070 was at 10%, but a rise of 5% is predicted due to climate change alone, then the net change would be a 5% decline.

Any changes in the levels of macro-nutrients and of the potentially associated minor and trace nutrients have the potential to affect natural ecosystems, which often have narrow and typically low nutrient level regimes (e.g. low phosphorous levels). Where significant increases (for example 10% or more) are demonstrated, it is likely that native ecosystems may be affected through introduction of environmental weeds and alterations in floral and faunal compositions. These are issues that may need to be considered and addressed by managers of these ecosystems. The alpine areas are particularly vulnerable.

The source of the predicted increased levels of these basic cations deserves consideration. They may be derived from wind borne dust and salts, particularly calcareous material, with the cations not being leached down the profile to the extent they currently are due to the projected drier conditions. Alternatively, the cations may be more slowly mixed and incorporated from the parent material at the soil base, but this would normally require a longer time scale than applied in this study. Further research on this issue is desirable.

5. Summary and conclusions

This study has provided predictions of the changes in key soil properties over New South Wales due to projected climate change over the next five to seven decades, based on 12 different climate change models. SOC, pH and sum-of-bases (common macro-nutrients) have all been examined over two depth intervals: an upper (0 to 30cm) and a lower (30 to 100cm) interval.

The 12 different climate change models adopted by the NARCliM program each presented a different scenario. These were applied over two change periods (about 2000 to 2030 and 2000 to 2070). Although all models tend to reveal a warming climate with increasing temperatures, there is considerable variation in trends with respect to annual rainfall, with the MIROC and CCC models projecting more moist conditions over New South Wales and the CSIRO and (to a lesser extent) ECHAM models projecting drier conditions.

The final predictions and spatial arrangement of the soil property changes across New South Wales vary with the different models, although the broad trends are generally uniform. By utilising the mean results from the 12 models we have revealed important broad trends and spatial patterns of change. The patterns of change vary across different parts of the State, depending on the combination of projected temperature and rainfall change and on environmental factors dominating different regions, i.e. current climate, parent material (reflecting soil fertility class) and land use. The modelling did not include the influences of ongoing land management practices over agricultural lands, only the influence of changing climate was considered.

From the average of the 12 models the following broad changes are apparent (from the projected climate change alone):

- SOC stocks are projected to decline over the State, typically varying between 0 to 10t/ha loss, but reaching a maximum decline of over 20t/ha in the southern alpine region.
- An increase in pH (i.e. becoming more alkaline) is projected over the State, generally increasing from east to west. The southern alpine region displays the greatest increases of up to 0.5 pH units or more.
- An increase in sum-of-bases (reflecting macro-nutrients) is projected over the State, typically varying between 5 to 20%. As for pH, there is a general increase from east to west and in higher areas. The far southern alpine regions display the greatest increases of up to 30% or more.

The predicted changes in these three soil properties have implications for the future health and character of NSW soils, and consequent effects on agriculture, natural ecosystems and climate change mitigation strategies. The combination of changes for the three soil properties should be considered, rather than just considering each property in isolation.

Soil condition and agricultural productivity generally all improve with the increase in organic content caused by the enhancement of physical, chemical and biological properties. They generally also improve with increasing pH (alkalinity) and macro-nutrient content across much of New South Wales, but this depends on the desired pH and nutrient ranges of different crop and pasture species. Significant changes in pH and macro-nutrient levels may also indicate significant changes in other minor and trace elements, with associated impacts on fertility and toxicity levels (Hazelton & Murphy 2007; Russell & Russell 1988). Thus, consideration of the changes in these three soil properties provides potentially important guidance for the productive management of agricultural soils across New South Wales in future decades (Stokes & Howden 2010). It is important to recognise that ongoing land management practices over agricultural lands may have stronger influence than the changes brought about by the climate change alone. For example, agricultural induced acidification (Fenton and Helyar 2007) may counter the trend towards alkalinity projected in this analysis.

Changes in soil properties – particularly pH and the levels of macro-nutrients and associated minor and trace elements – may affect natural ecosystems, which often have narrow chemical tolerance ranges. Where significant increases or decreases are revealed it is likely that native ecosystems will be affected through the introduction of environmental weeds and alterations in floral and faunal compositions (Steffen et al. 2009; Prober & Wiehl 2012). These are issues that may need to be considered and addressed by managers of these ecosystems – for example, through increased weed management programs and by allowing for the gradual migration of ecological communities to areas with the required soil conditions. Unlike in agricultural systems, these soil changes might be difficult to counteract with active management measures. Alpine regions may be particularly vulnerable to such changes as species migration is typically more limited.

The results for SOC also have implications for climate change mitigation programs that are based upon increased soil carbon sequestration (Lal & Follett 2009; Wilson et al. 2011; Baldock et al. 2012). The predicted decline in soil carbon storage levels across virtually the entire State suggests even greater carbon-enhancing actions will be required to produce the desired soil carbon increases, particularly in those regions where a large decline is predicted.

In examining the results of this study and deriving conclusions, one needs to consider several potential weaknesses and complicating issues. Inherent uncertainties exist in the modelling process: they include the use of a linear rather than non-linear modelling approach; the representativeness of sites used in the training data set; laboratory data inconsistencies; minor extrapolation of models beyond the climate range of the original training data; and inaccuracies in the covariate grids used for final map production. These weaknesses are reflected in the low validation statistics as presented in Table 2. There are uncertainties in the validity of the different climate projections applied, particularly with respect to the significant variations in annual rainfall projected by the different global and regional models.

The non-incorporation of ongoing and adaptive land management practices is a shortcoming of the analysis. The modelling did not consider the period required by soils to re-equilibrate with changing climatic conditions (Baldock et al. 2012); this may involve periods of decades or more, particularly for pH and macro-nutrients. No account was taken of other related impacts associated with climate change, such as likely changes in land use and management practices, vegetation patterns, erosion hazard, fire regimes and seasonal climatic patterns, all of which may affect soil conditions. Soil carbon dynamics are particularly complex, with uncertainty in the level of vegetation growth arising from increased atmospheric CO_2 levels and from changes to regional soil–atmosphere carbon exchange processes (Ostle et al. 2009).

Despite these potential weaknesses and sources of uncertainty, the results of this study provide a useful first approximation of changes in three important soil properties resulting from climate change across New South Wales over the coming decades. They should help managers of agricultural and native vegetation ecosystems landscapes across the State to more fully prepare for the expected changes in soil conditions. They may provide valuable inputs into many important environmental modelling programs, including climatic, ecological and agricultural models. More generally, the results add to our knowledge and understanding of how soils, a vital resource for humankind, may change with anticipated climate change.

Glossary

Chromosol – a soil characterised by a loam topsoil overlying clay-rich sub-soil; from the Australian Soil Classification System of Isbell (2002).

Coefficient of determination (R^2) – a statistical parameter that describes the strength of a relationship, with 0 indicating no meaningful relationship and 1.0 indicating a perfect relationship.

Covariate – an environmental variable used in the regression models, such as annual rainfall, annual maximum temperatures and silica %.

Digital soil modelling and mapping (DSMM) – soil modelling and mapping approaches that use statistical tools, computers, geographic information systems (GIS) and existing spatial environmental datasets to prepare statistical models and electronic soil maps. Outputs are typically continuous raster grids rather than polygonal maps of conventional soil mapping programs.

Kandosol – a soil characterised by textures that gradually increase in clay content with depth; from the Australian Soil Classification System (Isbell 2002).

Kurosol – a soil characterised by a loam topsoil overlying clay-rich sub-soil that is strongly acid (pH_{water} <5.5 or about pH_{CaCl_2} <4.5); from the Australian Soil Classification System (Isbell 2002).

Lin's concordance correlation coefficient – a statistical parameter that describes how close predictions are to observed values (i.e. a 1:1 line), with values of 0 indicating no predictive ability and 1.0 indicating a perfect predictive ability.

Organic carbon (OC) – carbon derived from living or dead biotic material, in contrast to inorganic carbon such as that from carbonate materials.

pH – a measure of acidity or alkalinity on a 1 to 14 scale, relating to the relative abundance of the hydrogen (H^+) cation. A pH value of 7 is neutral, values below are acidic, and above this alkaline. pH values measured in calcium chloride are typically 0.5 to 1.0 units less than those measured in water (Hazelton & Murphy 2007). Plant growth is generally impeded at pH less than 4.5 (acidic) or greater than 8.0 (alkaline) (NSW Agriculture 2000).

Rudosol – a soil characterised by a lack of soil profile development, apart from some topsoil development. In the Sydney region they are typically shallow and contain significant volumes of rock; from the Australian Soil Classification System (Isbell 2002).

Sum-of-bases – the combined total of the exchangeable cations calcium, magnesium, potassium and sodium in the soil (i.e. a subset of common macro-nutrients) available for uptake by plants.

Tenosol – a soil characterised by uniform sandy or loamy textures throughout the profile; from the Australian Soil Classification System (Isbell 2002).

Vertosol – a soil characterised by uniform clay textures throughout the profile; from the Australian Soil Classification System (Isbell 2002).

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