Soil science in the management of multi-functional rural landscapes

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Abstract
Communities are concerned that we manage our landscapes to provide economic, social and environmental services for the future. Governments are making major investments in changing land use and seeking to improve land management. We describe a bio-economic approach for planning agricultural land use to meet multiple objectives. The analysis enabled quantification of the extent of different types of land use change required to meet salinity and water yield targets at least economic cost, and where land use change should best occur within a landscape. This and other land use planning approaches require knowledge of at least the distribution of soils, the surface and groundwater hydrology, the current land use, economic costs and returns of current and proposed land uses, and landholder capacity to change. Advances in digital soil mapping, proximal sensing, application of airborne geophysics, digital elevation models, terrain indices and land use mapping are reducing the cost of data acquisition. This facilitates better utilisation of modelling capacity in land use planning.

Key Words
Land use, planning, mapping, terrain analysis, agriculture, salinity.

Introduction
Rural landscapes in many parts of the world are changing from predominantly agriculture and forestry production to delivering an increasing number of other functions including environmental conservation, provision of water for consumptive use, carbon sequestration, infrastructure development, supply of raw construction materials, waste disposal, recreation, cultural values and space for housing. Landscapes are complex; they include people and their biological and physical aspects are overlain by social, cultural and economic dimensions. The multi-functionality and complex structure of the landscape (e.g. Degórski 2003) emphasises the need for interdisciplinary landscape research to support sustainable land development.

Sustainable rural land use must protect the natural resource base while maintaining an acceptable local economy and social conditions. Successful rural land use planning requires: i) demand and goal oriented identification of land use functions, ii) participative negotiations on possible land use combinations involving all groups, including science, and iii) an iterative decision making process that tolerates uncertainties and adapts to emerging information and knowledge (Wiggering *et al*. 2003). Science has a role in achieving sustainable land use - providing advice to the decision makers as part of a broad consensus-driven process.

Soil science can contribute to the multidisciplinary approach necessary to help us manage our landscapes well. Land use planning is driven by the spatial distribution of functional land attributes which dictates suitability for different uses. Soil processes and soil-plant-atmosphere interactions are at the centre of interdependencies between land use and landscape function. Quantitative land evaluation provides a useful integrating framework.

This paper outlines an approach to multi-objective land use planning by i) describing a bio-economic approach for planning agricultural land use to meet catchment salinity and water yield targets at least cost, ii) highlighting the important role of soil science in multiple objective rural land use planning, and iii) describing key soil and terrain data needs and recent advances in meeting those needs.

Bio-economic analysis - targeting farm scale land use change to reduce catchment salt load
In southern Australia, replacement of deep-rooted perennial vegetation with shallow-rooted annual crops and pastures has caused increased deep drainage, rising groundwater levels, and subsequent land and river salinisation. Successful management of salinity, including achieving adequate return on investment into

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salinity mitigation, is measured at the catchment scale. However, catchment scale responses are the result of action by individuals at the paddock or farm scale. Much salinity research in Australia has not adequately linked farm and catchment considerations. This study sought to assist farmers and catchment managers target investment in land use change so catchment salt and water targets could be met at least cost.

Materials and methods

Simmons Creek is located on the eastern Riverine Plain, north east of the township of Walbundrie in southern New South Wales, Australia. Approximately 98% of the 178 km^2 catchment is used for agriculture, mainly mixed cropping. Local farmers helped identify 8 broad classes of land use. Typical gross margins were calculated for each component (e.g. wheat or lucerne) of each land use, averaged over ten years to produce an annual gross margin ($/ha/year). The Agricultural Production Systems Simulator (APSIM) (Keating *et al*. 2003) was configured to simulate the crop/plant growth and water balance of each of the land use scenarios on each of five soil types found in the catchment (i.e. a matrix of 8 land uses x 5 soil types). Simulations used climate data from 1891 to 2006 (116 years). The APSIM model supplied estimates of run-off, drainage and gross margin from each land use and soil to a linear programming (LP) model.

The LP model calculated minimum-cost changes in land use to attain specified targets of future salt-loads and water-yields from the catchment. The model incorporated 13 sub-catchments with various levels of connectivity reflecting the conceptualisation of the catchment's hydrology (English *et al*. 2002). Within sub-catchments, the model accounted for lateral fluxes of surface water down-slope thereby changing the productivity and water balance of the land receiving run-on. Deep drainage and groundwater processes are considered at the sub-catchment scale. In the lower (southern) parts of the landscape deep drainage discharges as baseflow at a specified fraction of the salinity of the groundwater beneath that sub-catchment.

The LP modelling estimated: 1) changes to current land use extent and distribution that would maximise farm income (i.e. maximise catchment gross margin) while maintaining current salt export, and 2) the progressive changes in land use extent and distribution that would be required for least-cost reduction from current estimated salt export (10,000 t salt/year) to zero (in 1000 t salt/year steps).

Results and discussion

The model selects an arrangement of land use that preserves as much highly profitable agriculture as possible while meeting prescribed salt load and water yield targets (Cresswell *et al*. 2009). Seeking greater reduction in salt load shifts land used for pasture into tree growing, and then as a last resort, land used to grow highly profitable rotational crops is shifted into growing trees. Shifts in land use to reduce salt export from the catchment progressively reduce farm income from the maximum achievable catchment gross margin (~$3M) - although the reductions in gross margin are modest (< 5%) until annual salt load has been halved to 5000 t. For reductions greater than this the marginal cost (cost per each extra tonne of salt load reduction) of reducing salt load gets progressively more expensive as greater reductions in salt load are sought.

Most of the land use change (both in area and degree) suggested by the modelling is in a few sub-catchments in the south of the catchment. These are the sub-catchments underlain by saline groundwater and where reducing deep drainage will have the most direct impact in reducing salt load. The changes are to replace cropping rotations with tree plantations in saline catchments while maintaining water yield by adopting higher water yielding land uses, such as annual pastures, in non-saline catchments. These changes result in loss of income. Most of the cost of salinity management within the whole catchment would be borne by only a few farms; the majority of the catchment remains unaffected until high levels of salinity mitigation are sought. However, since our analysis estimates the cost of these land use changes, it could form the basis to negotiate cost sharing between the relevant parties.

There is considerable uncertainty in the 'current' baseline salt load contribution from Simmons Creek catchment. This translates to uncertainty in the unit cost ($/t) of salt mitigation. However, the sequence of land use change for least-cost meeting of salt targets remains the same, no matter what value is assumed for baseline salt load.

The careful targeting of changes in land use is essential for cost-effective salinity mitigation in this landscape. There are many locations in Simmons Creek catchment where land use change would not be effective. In fact, land use change to achieve reductions in salt load could easily cost more than the apparent value of benefit derived. This situation can be avoided by undertaking appropriate economic analysis as part of salinity management planning.

This analysis should not be seen as providing any sort of prescription for land use change, rather as a component input into a broader landscape planning process.

Reducing soil and terrain data constraints for multi-objective rural land use planning
Multiple objective land use planning requires soil, terrain and land use information. The ready availability of such data in Australia has been a constraint. Recent research has sought to address this as shown by the examples below.

Digital elevation models and terrain analysis
A new one-second digital elevation model (DEM), covering the whole of Australia, has been derived from space shuttle radar elevation data following a rigorous process of correcting for vegetation influence and other artefacts (JC Gallant *pers comm.* 2009). High resolution laser altimetry data is also available in some areas. DEMs and terrain indices such as the multi resolution valley bottom flatness index (MrVBF, Gallant and Dowling 2003) are used in delineating catchment boundaries, indicating hydrological flow direction, spatial landscape disaggregation, landscape stratification for biodiversity, and in digital soil mapping.

Digital soil mapping (soil functional attributes and their distribution)
Soil data for Australia is sparse and conventional survey is expensive and time consuming. New digital soil mapping technologies are showing much potential for broad scale application. McKenzie and Gallant (2007) combined the use of airborne gamma radiometrics data with the MrVBF terrain index and a conceptual model of landscape evolution to effectively map soil profile classes and assign functional soil attributes such as soil depth and water holding capacity to each class. The resultant data is required, for example, in prediction of the soil water balance, assessing land suitability for alternative agricultural systems, and predicting commodity production.

Proximal soil sensing
Functional soil attributes will soon be able to be inferred and mapped efficiently using new proximal sensing of visible and infrared spectrometry (Viscarra Rossel *et al*. 2006), electromagnetics and gamma radiometrics (Wong *et al*. 2009). Complementary sets of sensors will be used together with spectral libraries to enable estimation of mineral and organic content and composition, as well as related properties such as cation exchange, pH, salinity, available water capacity and bulk density. Predictions of functional attributes of soil and their spatial variation will enhance digital soil mapping for the purposes listed above.

Mapping land use and land management
Nationally consistent land use mapping at ‘catchment’ (1:25 000 – 1:250 000) and ‘national’ (approximately 1:2 500 000) scales is available for Australia (BRS 2006). Improved satellite image classification techniques are being used to classify land cover, land use and management practices (e.g. use of contour banks). Satellite remote sensing time series enable regularly updated land cover and fractional cover data that assists in the mapping of land use and key attributes linked to management (such as ground cover levels).

Surface and groundwater hydrology
As with soil mapping, a robust underlying conceptual model is an essential precursor to accurately representing surface and groundwater hydrology, including salinity processes if required, in studies of landscape process. Advanced terrain analysis (above) is enhancing understanding of surface hydrology. Airborne geophysical survey (e.g. English *et al*. 2004) is giving new insights into regolith structure and salt stores, and helping guide design of complementary groundwater monitoring and drilling.

Conclusion
Land use planning that utilises biophysical modelling and economic optimisation is only likely to be required in areas where large investments and/or changes in land use are to occur. Other circumstances warrant simpler approaches. Spatial multiple criteria analysis (MCA) is a useful land use planning approach (e.g. Hill *et al*. 2006). MCA is very well suited to a structured synthesis of information from people with relevant domain knowledge within a participative mode of operation. MCA can use modelling input and can incorporate social metrics such as landholder preferences and capacity to change, especially where these can

be quantified spatially. If more explicit cause-effect analysis is required then biophysical model predictions, economic gross margins, and knowledge from conceptual models of landscape function can be used together to add significant understanding. The integration (planning) framework is necessarily spatial and chosen to meet the needs of the local stakeholders. An essential prerequisite for this type of analysis is prior investment in understanding the catchment basics - including the distribution of soils, the surface and groundwater hydrology, the current land use, economic costs and returns, and landholder capacity to change. Soil science has an essential role in integrative landscape analysis including through reducing the cost of soil data acquisition and improving understanding of soil distribution and function.

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