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Research, part of a Special Feature on Applying Landscape Science to Natural Resource Management

Dynamic land cover information: bridging the gap between remote sensing and natural resource management

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ABSTRACT. Environmental decision-makers are increasingly demanding detailed spatial coverages with high temporal frequency to assess trends and changes in the extent and condition of wetlands, species habitats, farmlands, forests, rangelands, soil, water, and vegetation. Dynamic land cover information can substantially meet these requirements. Access to satellite-based time series information provides an unprecedented opportunity to better focus natural resource management (NRM) in Australia. Opportunities include assessing the extent and condition of key assets, prioritizing investment in key localities and time periods, improving targeting of scarce public funding, and monitoring and evaluating the outcome of this investment to assist land managers in improving land management practices to meet wider community social, economic, and environmental goals. We illustrate how these key "decision points" can be enhanced by linking dynamic land cover information to a stepped "cycle" model. We use the stepped cycle model to present two case studies, the management of fire and soil erosion, which demonstrate the application of dynamic land cover information to improve NRM decision-making across three broad stakeholder groups (national, regional, local). We use the case studies to highlight how accurate dynamic land cover information has been used to improve the design and reporting of national NRM programs.

Key Words: *dynamic land cover; fractional ground cover; imagery archives; land management practices; natural resource management outcomes; on-ground actions, remote sensing*

INTRODUCTION

Land use and management activities have transformed much of the forest and woodland landscapes of Australia's eastern ranges and the southeast and southwest of Australia. Large areas have been cleared and converted to crops and pastures or transformed ecologically by 150 or more years of livestock and forest management (Thackway and Lesslie 2008, Williams and Price 2010). The resultant landscapes are a diverse mosaic of fragmented and modified native vegetation and converted and replaced land cover (Dovers 2000, Lymburner et al. 2011).

While these land cover changes have greatly benefited Australians, in some ways they have also reduced the productive ability of natural resources (Thackway et al. 2006). Monitoring these changes is therefore a pressing concern for all levels of Australian governments.

Atyeo and Thackway (2006), National Land and Water Resources Audit (2007), Lymburner et al. (2011), and Chu et al. (2011) summarize the various needs for consistent and thematically comprehensive land cover information at a range of temporal and spatial scales to:

- evaluate the impact of investments and resource condition monitoring under the Caring for our Country program (for issues such as salinity, water, soils, native vegetation, inland aquatic, and native species);
- distinguish whether the changes observed are due to climate variability or human-induced influences;
- report on changes in forest cover and the effect on carbon emissions through the National Carbon Accounting System's Land Cover Change Program;
- inform legislated State of the Environment reporting on vegetation condition and extent, and the condition of our land and soils and biodiversity;
- undertake water accounting required under the *Water Act* (2007) by the Bureau of Meteorology;
- monitor management of farms, catchments, and forests; and
- assess responses of native vegetation systems to disturbances such as cyclones, fires, and droughts.

It is difficult to develop a cohesive picture of land cover dynamics at different spatial and temporal scales using traditional land parcel and survey-based land cover mapping methods due to the time and cost required for field data collection. A further complication is that land use and management practices change over time, reflecting different social, economic, and environmental influences (Hamblin 2000, Foley et al. 2005, Lesslie et al. 2011, Lymburner et al. 2011). Practices within land uses also change. For example, many graziers now adopt more scientific approaches to

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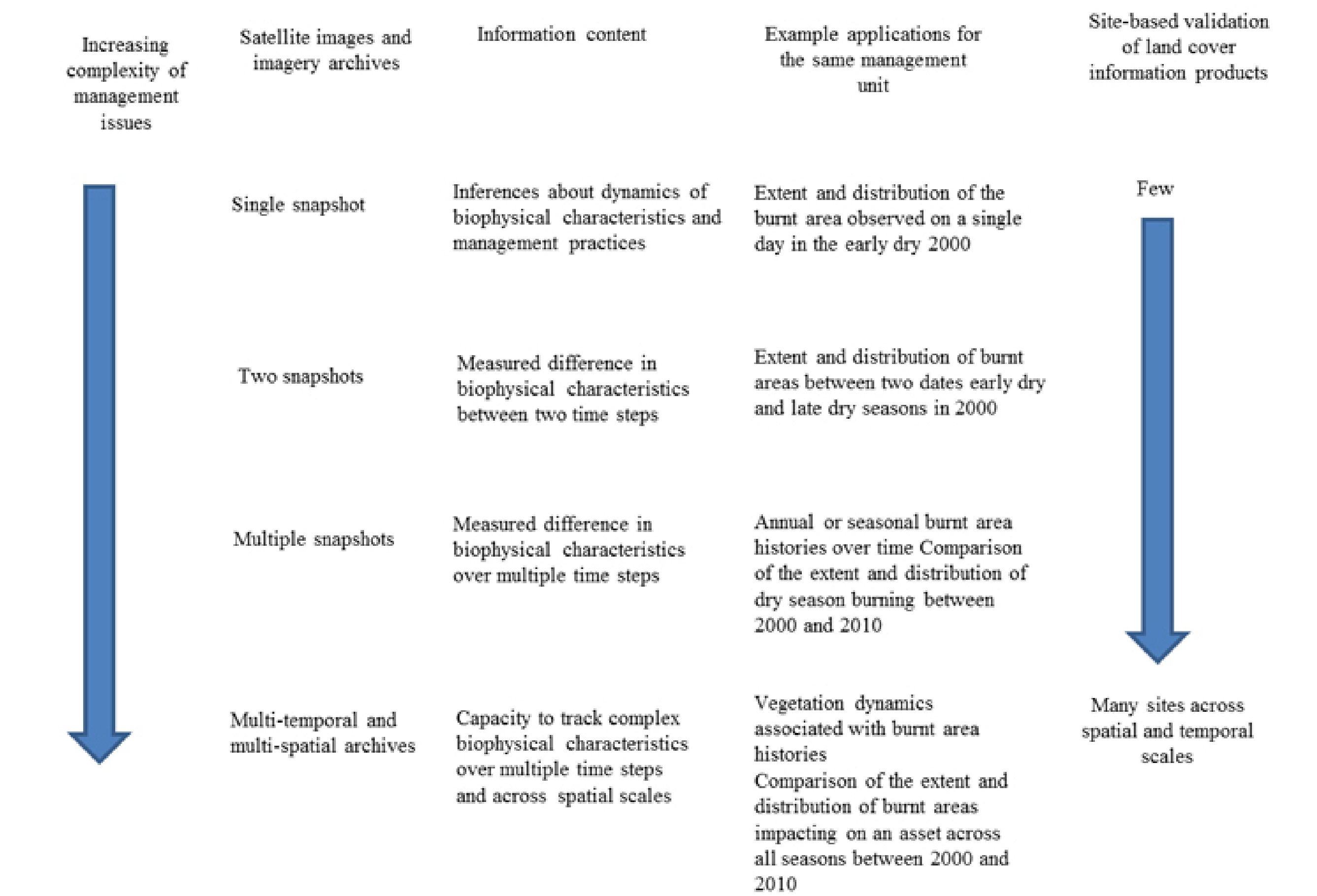
Fig. 1. Different land cover products are developed with different levels of detail and complexity for different purposes, e.g., fire management.



stocking levels, and conservation tillage is more commonly used (State of the Environment Committee 2011). Given the diverse nature of natural resource management, remote sensing systems that provide a range of spatial, temporal, and spectral resolutions are required.

We describe a stepped "cycle" model that links decision-makers operating at different spatial and temporal resolutions with the types of land cover information products they require. We present two case studies using this stepped cycle model—one concerning fire, and the other concerning soil erosion. We discuss the lessons from these case studies, highlighting the benefits of developing multi-temporal biophysical characterizations of the earth's surface over time, building on the foundation of multi-sensor earth observation archives combined with systematic ground-based measurements. We illustrate how the stepped cycle model and dynamic land cover information can be used to address the range of complex social-ecological relationships involved in natural resource management (NRM) and monitoring.

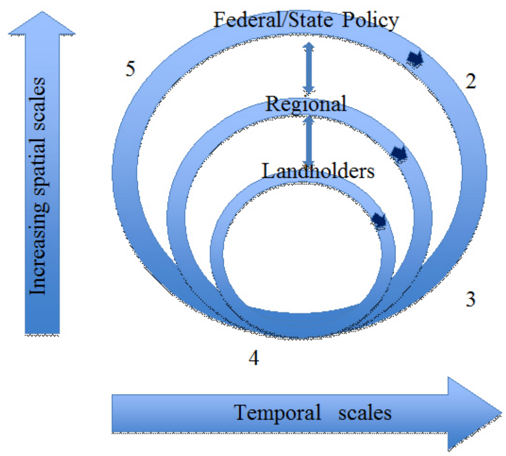
USE OF LAND COVER INFORMATION

Framework for managing information needs of natural resource management decision-makers

A wide range of land cover products is generated for different NRM applications to meet different levels of detail and complexity. Figure 1 describes some of these land cover products, using fire management as an example.

Three broad stakeholder groups of NRM decision-makers require land cover information: public policy and program managers (e.g., federal and state governments), regional bodies (e.g., Catchment Management Authorities), and land managers (Fig. 2). Together, these decision-makers are aiming to deliver improved NRM outcomes through adaptive management. There are interactions and crossovers between the different stakeholder groups. Figure 2 illustrates these interactions with varying spatial and temporal scales, and a corresponding set of five broad decision steps or points.

Fig. 2. Nested natural resource management decision-making cycles interacting across the actions of decision-makers at varying spatial and temporal scales and corresponding to the set of five broad decision steps or points in the stepped "cycle" model.



Steps or decision points for managing land cover outcomes

Step 1: Asset definition - Determine the appropriate landscape scale, characterize the mosaic of land cover types and their ecosystem function (when and where).

Step 2: Identify land cover characteristics - Determine the extent that the required ecosystem services are supplied by the current land cover classes and their ecosystem function and assess how the social-ecological setting supports and/or limits their capacity.

Step 3: Identify needs for change - Determine if and where in the landscape changes in land use or management actions will maintain or enhance the condition of land cover assets and hence improve the mix of ecosystem services.

Step 4: Identify and select options and implement priority actions - Set priorities for actions, consider trade-offs involved, and identify areas for intervention where actions are to be undertaken through existing, revised, or new policy and/or changes in management practices. Invest in interventions that match selection criteria and monitor land cover responses and links to ecosystem services and the effects of investments; integrate relevant monitoring data with existing database systems.

Step 5: Evaluate the responses of the land cover to actions - Analyze the spatial and temporal patterns and how well the outcome met the desired goals and targets. Repeat steps 1-5 as required.

Source: Steps 1-5 are modified from Yapp et al. 2010.

For example, climatic drivers can be used to manage the expectations of the three stakeholder groups with appropriate land cover information using a stepped cycle model, described in Figure 2. It is also important to note that this is true at both the landholder time frame as well as the regional and federal/state time frames. For example, individual land holders need this information at steps or "decision points" 3 and 4 of Figure 2—i.e., at the time when they are planning to implement the next land management practice—e.g., whether to irrigate, retain stubble, or destock or hang on and hope the rains arrive. In contrast, regional, state and federal stakeholders require the climatic reference frame in step 5 when they are assessing the efficacy of the policy/investment.

Decision-maker groups depicted in Figure 2 will ultimately choose the imagery that fits their purpose and can be purchased, processed, and distributed for least cost and will minimize risk and adverse impacts. Ultimately, the choice of imagery involves a trade-off between temporal frequency and spatial resolution, and depends on the task at hand (see *Case studies*). The decision-maker's choice of spatial and temporal scales for selecting and utilizing a particular remote sensing product is also determined by their entry point into the stepped cycle model, depicted in Figure 2. If a decision-maker enters at step 1, then this is referred to as the baseline. If the decision-maker enters at steps 2 to 5, then the preceding step in the model influences the decision-maker's choice of spatial and temporal scales. For example, where a decision-maker enters at step 3, the decision-maker should refer back to step 2 to establish the basis and context of what land cover features were identified and described in order to match the particular remote sensing spatial and temporal scales of that step. This process encourages the development of methods for detecting and monitoring land cover change that are more consistent between different decision-makers and are more likely to be repeatable over time, acknowledging differences between remote sensing products, i.e., differing spatial and temporal scales.

While a range of decision-makers is engaged on the same environmental issue in most NRM land cover applications, they operate at different scales and therefore need a range of land cover products. In the past, disparate projects generated nonstandardized land cover products, which made it difficult to share information across different groups of decision-making. The development of national coverage land cover imagery archives at a range of spatial and temporal scales is increasingly providing much greater opportunities to develop and use complementary image-based products for these different groups of decision-makers.

We suggest that within the operating environment of these three broad groups (national, regional, local), a stepped cycle model (i.e., "decision points") can guide stakeholder and decision-maker understanding of what land cover information is needed and how it might be used. Five steps are presented: step 1: select key assets; step 2: identify the land cover characteristics of these assets; step 3: identify what needs to change and for what purpose; step 4: identify and select land management options and implement priority actions; step 5: evaluate the response of the interventions at a range of spatial and temporal scales. Such a model can be reviewed and repeated to assess progress toward immediate, short-, medium-, and longer term targets, or, as necessary, in response to changing environmental conditions or priorities. Noting that steps 1–5 are relevant across the three decision-maker groups highlights the complementarity between types of decisions and types of land cover products needed.

The stepped cycle model is flexible in that it enables continuous improvement within each of the steps to be investigated and implemented to provide a robust approach to adaptive management. In addition, the model may be used to demonstrate how issues of scale, accuracy, and reliability of data can best be understood and how this information can be used at each step of a strategic decision-making approach with different groups (national, regional, and/or local).

The shift toward dynamic land cover information

In reviews of research on the analysis and classification of land cover information methods and products that involved mapping land and ground cover types and their associated land use management systems, Lymburner et al. (2011) and Skidmore et al. (2011) note that multi-temporal image products are generally more accurate and informative than single image date products.

Given that land cover is constantly changing and that changes can be dramatic (drought versus wet year, ploughed ground versus full crop), a single snapshot image, although correct for that moment, cannot characterize the dynamic temporal nature of land cover. Even the interpretation of the change between two or three images can be difficult without knowing where in the "land cover cycle" the images were taken. Examples of this are images before and after rainfall, in a drought year and a wet year, and in a cropped year and a fallow year. For these reasons, systems are being developed providing decision-makers with dynamic land cover information that are designed to meet their information needs at key "decision points". The case studies below illustrate this using a stepped cycle model.

In proposing this stepped cycle model, we argue, however, that neither satellite imagery nor field-based approaches in isolation are capable of meeting these information requirements. Field monitoring and on-ground data collection regimes are costly and rarely cover the full range of land cover interactions. In many instances the data are collected for a specific purpose over a finite time frame, which limits the transferability of the results and makes it difficult to establish a longer term perspective. Satellite imagery, on the other hand, typically measures the amount of radiation that leaves the top of the atmosphere. Without appropriate field data, it is difficult or impossible to convert that imagery into the kind of biophysical information products needed by decision-makers.

Overcoming the inherent shortcomings of both data collection methods (i.e., time series satellite imagery and field-based) requires five key phases that each adds value to the imagery archives:

Phase 1. Precision geometric correction to enable per pixel comparison.

Phase 2. Convert top-of-atmosphere radiance to surface reflectance (removing the influences of atmospheric effects and sun-sensor geometry artifacts). This phase is also known as radiometric correction.

Phase 3. Correlate surface reflectance and the biophysical characteristic of interest to the NRM problem at hand, e.g., presence/absence of open water, amount of green or nonphotosynthetic vegetation cover or persistent tree cover, where these biophysical characteristics have been measured in the field in a robust systematic way, such as that described in Muir et al. (2011) or Armston et al. (2009).

Phase 4. Convert the satellite imagery into surfaces that represent biophysical surfaces based on the relationship established in Phase 3.

Phase 5. Collate these biophysical surfaces to enable end users to assess where and how features that interest them have changed over time.

A number of NRM-related time series imagery archives have been developed to assess, monitor, and report land cover changes and trends (Table 1). Land cover themes covered by these dynamic applications include extent of, and change in, forest and vegetation, burnt area and presence of fire, and ground cover. The remote sensing archives include Landsat, MODIS, and AVHRR, thus illustrating a range of image resolutions.

Case studies

Two resource management case studies that have benefited substantially from access to consistent standardized satellite image archives are the management of fire and ground cover. Both case studies have addressed the interactions between climate and land management, and they demonstrate the value of developing a monitoring program to provide appropriate spatial and temporal products, many ground control sites and modeled and/or remotely sensed validated data, and information products at a range of scales. In addition, they both use an indicator framework, which provides a sound basis for assessing status, change, and trend. These case studies represent state-of-the-art long-term spatial and temporal monitoring and are underpinned by systematic field-based observations that are used to calibrate and test the models and assess the accuracy of the information products.

We note that the fire case study has been running longer than the ground cover case study. As a result, it is evident that the fire case study has completed several iterations of the stepped cycle model compared to the ground cover case study.

Case Study 1—Managing fire in northern Australia

Much of Australia's northern savannas are fire prone and extensively used by pastoralists, Aboriginal landholders, and conservation managers for many cultural, economic, and ecological purposes (Murphy et al. 2009).

Table 1. Examples of applications of time series imagery archives.

Natural resource management application	Study name	Land cover theme(s)	Output classes	Sensor	Time frame	Key reference
Bushfire management	Wildfire mapping and monitoring in Australia's northern savannas	Closed forest, open forest, woodland, heathland, shrubland, grassland, sedgeland, and other cover types	Burnt area	Landsat, MODIS & AVHRR	1980s–present	Murphy et al. (2009)
Soil erosion management	Dynamic Land Cover Dataset	Crop, sugar, trees, shrubs, graminoids, and other cover types	ISO land cover classes	MODIS	2000–present	Lymburner et al. (2011)
Losses and gains in tree cover for carbon accounting	National Carbon Accounting Scheme	Tree cover	Forest/nonforest	Landsat	1980s–present	Caccetta et al. (2007)
Losses and gains in tree cover for carbon accounting	Statewide Land and Tree Clearing Survey	Tree cover	Forest/nonforest	Landsat	1980s–present	DERM (2010)
General application for natural resource management monitoring and reporting	Fractional Cover Dataset	Green vegetation, dead vegetation, and bare ground	Percent of different ground cover types	MODIS	2000–present	Guerschman et al. (2009)
Bushfire management	Sentinel hot spots	Thermal hot spots	Hot spot	MODIS	2000–present	Australian Government (2011)
Modeling the extent of woody vegetation	Fraction of absorbed photosynthetically active radiation (FAPAR)	Tree cover	Persistent FAPAR/ recurrent FAPAR	AVHRR	1980s–present	Donohue et al. (2009)

In the 1980s, Australia's northern savannas, other than Kakadu National Park, lacked a coordinated fire and land cover mapping and monitoring program (Thackway and Olsen 1999). This was partly because there was little understanding of, or concern for, fire effects.

By the early 1990s, a number of Commonwealth, state, and territory government reports were raising concerns about the vast areas of northern savannas that were being burnt by largely uncontrolled fires late in the dry season under severe fire-weather conditions (Head et al. 1992, McDonald and Batt 1994, Rose 1995, Russell-Smith et al. 2000). The primary issues of concern included the effects on cultural, economic, and ecological sustainability. More recent research shows that these fire regimes damage natural ecosystems and produce significant greenhouse gas emissions (Murphy et al. 2009).

The formative program of research, monitoring, and reporting land cover and seasonal patterns of fire in Kakadu commenced in the early 1980s, with the aim of promoting better cultural, economic, and ecological sustainability outcomes for the 20,000 km^2 park (Russell-Smith et al. 1997). The results were used to inform work plans and research budgets, and to evaluate cultural, economic, and ecological sustainability objectives outlined in management plans. By 1990 the benefits of this program were recognized, and the program was adopted in two nearby national parks. The main elements of the program were subsequently adopted across northern Australia (Russell-Smith et al. 2007). The social, economic, and environmental benefits accruing from the coordinated program of fire and land cover mapping across northern Australia have earned national and international recognition.

The original aims of the research, underpinned by land cover mapping, were to help understand the effects of annual fires on regional biodiversity and to develop management guidelines and strategies for the long-term maintenance of biodiversity. Over time the aims have expanded to develop an understanding of effects on regional biodiversity, environmental patterns and trends, greenhouse gas emissions, human health, and social and community values. Today these programs have the cooperation of many public and private organizations that represent all major land-use sectors and the rural fire management agencies (Murphy et al. 2009).

The key components of the northern savanna land cover and fire monitoring program are summarized in Table 2 using the stepped cycle model.

Case Study 2—Managing ground cover in cropping areas and rangelands

Large areas of Australia are managed for grazing and cropping, which involve the use and management of ground cover to produce a range of ecosystem goods, including food and fiber. Wind and water erosion remove valuable top soil, which adversely affects rural communities, biodiversity, carbon stores, and our ability to produce food and fiber (Leys et al. 2009).

Table 2. Case study—The role of dynamic land cover information in managing fires in Australia's northern savannas.

Monitoring and reporting steps	Examples of the analyses used to create fire and land cover information products	Examples of information needed to manage fire
STEP 1: ASSET DEFINITION Determine the appropriate landscape scale, characterize the mosaic of land cover types and their ecosystem function (what, when, and where)	Create an imagery time series using a remote sensing imagery archive, 1990 onwards, including AVHRR, MODIS, and Landsat. Use this series in combination with other environmental, social, and economic information to: • Classify and map land cover using an appropriate land cover classification system • Classify and map fire-affected areas at different scales • Define key assets different spatial and temporal scales, including threatened communities and sensitive areas • Develop and test indicators—e.g., percent area burnt in early dry season and late dry season, and frequency of burning • Establish fire plots • Collect field-based measurements of vegetation and habitat attributes and observed fire management	• Characteristics of assets within a regional context—e.g., what, where, when, and who manages the asset • Tables, figures, and maps on the known responses of land cover classes to fire management practices • Which land cover classes have biodiversity assets—e.g., threatened communities, sensitive areas • Fire regime of each land cover class—e.g., seasonality, intensity, and the responses over time • Key indicators—e.g., changes in percent area burnt in early dry season and late dry season, changes in frequency of burning between land cover classes, long-term declines in greenness indices • Positive and negative responses of vegetation and habitat attributes to fire management practices
STEP 2: IDENTIFY LAND COVER CHARACTERISTICS Determine the extent to which the required ecosystem function and services are supplied by the current land cover classes and their ecosystem function, and assess how the social-ecological setting supports and/or limits the capacity for amelioration	• Define appropriate fire regime responses for selected assets • Characterize the range of responses of land cover classes to seasonal rainfall patterns • Characterize changes and trends in fire-affected areas within land cover classes • Establish the links between responses of vegetation and habitat attributes over time under known land management practices—e.g., fire management • Establish the range of social-ecological responses within land cover classes at various scales and the capacity for amelioration	• Which assets and land cover classes have appropriate and inappropriate ecological responses over time • Which land cover classes are likely to exhibit limited capacity to change management practices or ameliorate impacts because of social-ecological settings
STEP 3: IDENTIFY NEEDS FOR CHANGE Determine if and where in the landscape changes in land use or management actions will maintain or enhance the condition of vegetation assets and hence improve the mix of ecosystem services	• Identify those land cover classes where the spatial and temporal responses are due to inappropriate management practices • Identify which areas are likely to respond positively to a change in land use or land management practices • Identify which areas have responded positively to a change in land management practices—e.g., areas where improved vegetation greenness over time is observed and correlated with improvements in the delivery of multiple ecosystem services	• Which assets and land cover classes exhibit unacceptable responses over time and are due to inappropriate management practices • Which assets and land cover classes are likely to respond positively to a change in land management practices • Short-, medium-, and long-term responses indicating the likely responses of vegetation and habitats to changes in land management practices • Relationships between ground-based practices and responses observed in remotely sensed imagery

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STEP 4: IDENTIFY AND SELECT OPTIONS AND IMPLEMENT PRIORITY ACTIONS Set priorities for actions, consider trade-offs involved, and identify areas for intervention where actions are to be undertaken through existing, revised, or new policy and programs and/or changes in land management practices. Invest in interventions that match selection criteria, and monitor land cover responses and links to ecosystem services and the effects of investments; integrate relevant monitoring data with existing database systems	• Identify those land cover classes and assets that are priority areas for intervention using changed management practices • Assess costs and benefits—i.e., trade-offs of intervening to change practices • Assess the least cost land management change options and maximum social benefit options for each land cover class • Provide field maps to engage the community and industry • Select ground-based reference and monitoring sites • Design and establish a field-based fire management monitoring system • Establish and monitor field plots over time, measuring responses in vegetation and habitat attributes and fire management practices • Integrate ongoing field-based monitoring with existing database systems • Negotiate work programs for areas to be treated • Identify assets to be avoided • Target areas for special treatment/s	• Priority areas to be treated using changed practices —e.g., early dry season burning on key landscape units within land cover classes • Costs of implementing particular fire management practices • Least cost options for intervening, and the likely social benefit in different social-ecological settings • Information to enable managers to accurately deploy priority actions in selected land cover classes and assets—e.g., early dry season burning • Near to real time remote sensing imagery to show what, when, and where an intervention was implemented
REPEAT STEPS 1–5 AS REQUIRED		

Ground cover (a component of land cover) is defined here as the material in contact with the soil surface that influences erosion rates (Leys et al. 2009). It includes trees and shrubs (woody vegetation); chenopod-type shrubs; crops, grass, and forbs; biological soil crusts; stone and rock; and other features, including fallen timber and litter. These components are not static in space or time. Ground cover varies depending factors such as geology, climate, and land management practices, and changes in response to seasonal, annual, and longer term natural and anthropogenic influences.

Ground cover protects the soil from erosion by reducing the impact of raindrops and reducing runoff and wind speed. Generally, the denser the ground cover, the lower the risk of soil erosion. However, nonwoody ground cover, such as crops, grass, forbs, and chenopod-type shrubs, is most closely linked to erosion rates and changes most over time (Leys et al. 2009). These are the components that farmers and graziers affect most and that best indicate erosion potential and land management performance (Leys et al. 2009).

Traditionally, remote sensing imagery has been used to monitor ground cover by estimating the amount of photosynthetically active material in the surface as a surrogate for vegetation cover. Vegetation indices, such as the Normalized Difference Vegetation Index (NDVI), were normally used to do that (e.g., Lu et al. 2003a). Such products were successfully incorporated into soil erosion models to estimate soil losses and trends (Lu et al. 2003b). The main difficulty with approaches based on the NDVI alone is that the nonphotosynthetic component of ground cover, which includes stubble, senescent herbage, and leaf litter, cannot be distinguished from the exposed soil; therefore, the effectiveness of the soil erosion modeling is reduced.

More recently, methods have been developed that resolve the green and nongreen components of ground cover (e.g., Guerschman et al. 2009, Okin 2010, Scarth et al. 2010). Those methods rely on longer wavelength properties of soils and dry vegetation than those used for the NDVI. Distinguishing between the nonphotosynthetic vegetation and bare soil improves the overall estimation of ground cover and therefore the ability of models to account for water and soil erosion. Additionally, such information can be used to infer land management practices (Leys et al. 2009). This is why time series imagery archives have been analyzed to inform decision-makers about the status of, and changes and trends in, ground cover. Ground cover information is generally a good indicator of land management and becomes increasingly useful when a time series is analyzed (Guerschman et al. 2009).

The value of a quantitative approach using spatially explicit time series data is that thresholds can be set to define which management practices are appropriate. For example, adequate cover levels at the end of a drought or dry spell in grazing county indicate appropriate stocking levels have been used, and high levels of stubble cover after cultivation indicate some form of stubble retention is being utilized (Leys et al. 2009). Leys et al. (2009) have shown that land management practices such as reducing cultivation and adopting rotational grazing methods can maintain higher levels of ground cover, minimize wind and water erosion, and reduce off-site costs.

The Australian Government's Caring for our Country program promotes adoption of land management practices that reduce the extent and severity of soil erosion across Australia. Continuous time series imagery archives are being developed to provide information to track the status of, and changes and trends in, ground cover achieved by this program in priority landscapes (Stewart et al. 2011). The method developed by Guerschman et al. (2009) has been selected to analyze the imagery. To ensure that the accuracy of ground cover estimates is known, field data from a diverse range of conditions need to be collected, up-scaled, and compared to model estimates. Once the degree of mismatch between observations and model predictions is clearly identified, improvements to the algorithms used to derive the biophysical properties of interest can be improved (Stewart et al. 2011). We acknowledge that this program is in its formative stages. Several complete stepped cycles (Fig. 2) will be needed to fully ascertain whether changes and trends observed in dynamic land cover were attributable to changes in land management practices that this program stimulated.

The key components of a national ground cover monitoring program are summarized in Table 3, using the stepped cycle model.

DISCUSSION

Increasing roles for dynamic land cover information

Multi-temporal and multi-spatial land cover information is particularly relevant to monitoring and reporting changes and trends in land cover information relative to baseline conditions in order to manage fires and soil erosion. The case studies show that land cover changes can be observed and tracked over time at a range of scales.

Access to comprehensive and consistent land cover change information is also essential to improve our understanding of the responses of natural systems to variable and extreme weather. Multi-temporal and multi-spatial land cover information helps decision-makers:

- target action to improve productivity, resilience to drought and climate variability, and water management;
- identify where investments in better management practices could improve the quality of ecosystem services delivered by agricultural land users;
- improve risk assessment and evaluate the performance of agricultural industries; and
- model landscape processes that affect the natural resource base and generate problems such as salinity, water quality decline, and soil loss.

Acquiring multi-temporal and multi-spatial land cover change information over large areas usually delivers consistent and repeatable information at a significantly lower cost than collecting the same information in the field. The cost per hectare to capture, process, and classify and distribute land cover information depends on the level of detail (spatial resolution) and the area being mapped. However, there is no substitute for repeatedly collecting information at sites (on-ground control and reference) in the field to classify and validate the land cover change information derived from time series remote sensing.

Multi-temporal and multi-spatial biophysical products derived from remote sensing can be used to help visualize, quantify, and analyze change in type and extent of land cover classes and to establish causal relationships with land use and management practices. Jones (2008) notes that up-to-date land cover information can be used for many purposes where knowledge of change and trend is critical; e.g., quantifying links between environmental pressures and drivers (e.g., increased water usage and conversion of agricultural land to roads and urban infrastructure); establishing baseline and change in landscape conditions; and understanding threats to, and vulnerabilities of, a wide range of environmental, social, and economic values.

For real on-ground change to happen, stakeholders across the NRM spectrum need to be able to access tailored, timely land cover information products that inform and support their decision-making processes. While archives of dynamic land cover information cannot meet all NRM information needs, satellite-based land cover products can provide:

- a framework within which to prioritize future interventions;
- a method to assess interventions that are likely to have affected canopy cover, grass cover, or bare soil cover; and
- an essential tool for delivering products to inform adaptive land management.

Using dynamic land cover information to inform decision-making

This section describes the role of land cover information for three stakeholder groups: national policy decision-makers, regional reporting decision-makers, and land managers.

Table 3. Case study—The role of dynamic land cover information in managing ground cover in Australia's cropping areas and rangelands.

Monitoring and reporting steps	Examples of the types of analyses used to create soil erosion information products	Examples of information needed to manage soil erosion
STEP 1: ASSET DEFINITION Determine the appropriate landscape scale, characterize the mosaic of land cover types and their ecosystem function (what, when, and where)	Create a time series of soil erosion histories using a remote sensing imagery archive—i.e., 1990 onwards, including AVHRR, MODIS, and Landsat. Use this archive in combination with other information to: • Classify and map land cover using an appropriate land cover classification system • Classify and map erosion-affected areas at different scales • Define key assets at different spatial and temporal scales, including areas at risk • Develop and test indicators—e.g., percent area classified as bare during the peak growing season • Establish ground control/reference sites • Collect field-based measurements of ground cover types	• Characteristics of assets within a regional context—e.g., what, where, when, and who manages the asset • Tables, figures, and maps on the known responses of land cover classes to erosion control practices • Which land cover classes have biodiversity assets—e.g., threatened communities, sensitive areas • Ground cover management regimes of each land cover class—e.g., grazing and cropping systems • Key indicators—e.g., long-term increases and declines in fractional cover indices • Positive and negative responses of ground cover to changed management practices
STEP 2: IDENTIFY LAND COVER CHARACTERISTICS Determine the extent that the required ecosystem function and ecosystem services are supplied by the current land cover classes and their ecosystem function, and assess how the social-ecological setting supports and/or limits the capacity for amelioration	• Define appropriate soil erosion thresholds and responses for selected assets • Characterize the range of responses of ground cover classes to seasonal rainfall patterns • Characterize changes and trends in erosion-affected areas within ground cover classes • Establish the links between responses of vegetation over time under known land management practices • Establish the range of social-ecological responses within land cover classes at various scales and the capacity for amelioration	• Assets and ground cover classes that have appropriate and inappropriate responses over time • Which land cover classes are likely to exhibit limited capacity to change management practices or ameliorate impacts because of social-ecological settings
STEP 3: IDENTIFY NEEDS FOR CHANGE Determine if and where in the landscape changes in land use or management actions will maintain or enhance the condition of vegetation assets and hence improve the mix of ecosystem services	• Identify those ground cover classes where the spatial and temporal responses are due to inappropriate management practices • Identify which areas are likely to respond positively to a change in land use or land management practices • Identify which areas have responded positively to a change in land management practices—e.g., observed improved enhanced vegetation index response curves and improved mix of ecosystem services	• Which assets and ground cover classes exhibit unacceptable responses over time and are due to inappropriate management practices • Which assets and ground cover classes are likely to respond positively to a change in land management practices • Short-, medium-, and long-term responses indicating the likely responses of vegetation and habitats to changes in land management practices • Relationships between ground-based practices and responses observed in remotely sensed imagery

(con'd)

STEP 4: IDENTIFY AND SELECT OPTIONS AND IMPLEMENT PRIORITY ACTIONS Set priorities for actions, consider trade-offs involved, and identify areas for intervention where actions are to be undertaken through existing, revised, or new policy and programs and/or changes in land management practices. Invest in interventions that match selection criteria, and monitor land cover responses and links to ecosystem services and the effects of investments; integrate relevant monitoring data with existing database systems	• Identify those land cover classes and assets that are priority areas for changed management practices • Assess costs and benefits—i.e., trade-offs of intervening to change practices • Assess the least cost land management change options and maximum social benefit options for each ground cover class • Provide field maps to engage the community and industry • Select ground-based reference and monitoring sites • Conduct regular monitoring and reporting of plot-based ground cover sites • Integrate ongoing ground-based monitoring with existing database systems • Negotiate work programs for areas to be treated • Identify assets to be avoided • Target areas for special treatment/s	• Identify investment priorities and opportunities to create a business plan • Identify high-value agricultural land to ensure it is protected through regional planning • Information needed to support regional natural resource planning and investment and strategies for industry development • Least cost options for intervening, and the likely social benefit in different social-ecological settings • Information to enable managers to accurately deploy priority actions in selected land cover classes and assets • Near to real time information showing what, when, and where an intervention was implemented
STEP 5: EVALUATE THE RESPONSES OF THE LAND COVER TO ACTIONS Analyze the spatial and temporal patterns and how well the outcome met the desired goals and targets	• Analyze the extent of a study area that has been successfully treated using other socioeconomic and environmental information • Analyze daily MODIS and AVHRR imagery to track the extent of a study area treated	• Extent of a study area that was successfully and unsuccessfully treated, and the reasons why—e.g., access constraints, training, cultural constraints • Which ground cover classes and assets were not adequately identified, and the reasons why—particular soil types and seasonal conditions • Which vegetation types and habitats responded over time in unexpected ways • Social-ecological benefits of the intervention/s—short-, intermediate-, long-term • Extent to which target/s were met (what, when, and where) • Identify key problem areas to restore soil function • Generate information to enable evaluation and reporting on soil condition indicators
REPEAT STEPS 1–5 AS REQUIRED		

National policy frameworks

Accurate national-level information about the way in which managed ecosystems respond to a range in drivers such as silviculture, forest fires, land clearing, and severe tropical cyclones is increasingly critical to inform NRM policies, ecosystem protection prioritization regimes, and carbon abatement strategies. As illustrated by the case studies, dynamic land cover information is capable of addressing this shortcoming and can provide many other benefits.

A key objective of public NRM programs is to track changes and trends in key assets over different time frames and at different spatial scales (Australian Government 2009). In addressing this challenge, the Australian Government's monitoring, evaluation, reporting, and improvement framework aims to ensure that appropriate monitoring of natural resources data is continuously collected and regularly reviewed to assess progress toward targets (Australian Government 2009). For example, to ameliorate soil erosion under the Caring for our Country initiative and to address the issue of causality, Leys et al. (2009) identified the need to make corrections in the land cover observations to account for climate when reporting resource indicators and management indicators. This monitoring framework also aims to reduce bias and error so that it can accurately report on the relationships between land cover change and soil condition.

Regional reporting frameworks
A systematic monitoring framework is fundamental to regional NRM bodies; it informs timely decision-making, supports measures of accountability, and provides a sound basis for evaluation and adaptive management. At this scale, monitoring is underpinned by on-ground observations, broader scale assessments, and adjustments in behaviors and practices.

Accurate identification of land cover change and trend is fundamental to understanding regional patterns of environmental degradation and/or improvements in land- and/ or ground cover-related indicators. Once these impacts are identified and their rates of change are understood and validated with on-ground observations, such information provides a sound basis for reporting and assessments, setting priorities, and monitoring progress toward targets that aim to improve or reverse the decline in an environmental indicator. We also acknowledge that some forms of environmental degradation and/or recovery can happen without many cover indices changing appreciably. Those that are must be informed by the collection of appropriate information at sites (on-ground control, reference, and monitoring) in the field (Jones 2008, Chu et al. 2011, Skidmore et al. 2011).

Combined with other regional scale environmental, social, and economic information, up-to-date information on the change and trends in burnt area and ground cover type and extent can be used to provide an early warning system to predict other direct and indirect impacts and to track rates of change. Both case studies illustrate the application of dynamic land cover to support regional decision-making.

Land manager decision-making processes
Dynamic land cover monitoring and reporting can provide the necessary spatial and temporal framework to help land managers raise questions and use available information to answer those questions. For example, have areas that behaved similarly in the past started to behave differently due to a new land management practice? Or where sufficient temporal baselines are available, has this area fared better during this drought than it did in the previous droughts? Contextual environmental information, such as comparative rainfall deficit, or climatic or hydrological factors, is also required to enable meaningful interpretation of fire and ground cover patterns.

Access to dynamic land cover information is improving land managers' ability to track land cover changes in response to major drivers such as climate change, NRM interventions, and environmental hazards, and to relate those changes to the delivery of key ecosystems services. The two case studies show that local fire and ground cover management decisions are informed by satellite-based archives.

Lessons for decision-makers
The use and management of natural resources changes land cover in ways that can usually be predicted. Of the many types of ecological disturbance, fire and vegetation water stress are amenable to remote sensing (DeFries 2008, Skidmore et al. 2011).

A key challenge for decision-makers across all three stakeholder groups is how to design and maintain enduring spatial and temporal information systems to identify changes and trends between the natural environment and the use and management of current landscapes, disturbance regimes, and climate variability. Application of the stepped cycle model and dynamic land cover information to the case studies of fire and ground cover management illustrates how these issues might be resolved more generally.

PMSEIC (1999) observed that a failure to recognize and understand the cause and effect of these changes—including lost production, increased costs of production, costs of rehabilitation, biodiversity losses, declining quality of air and water, and declining aesthetic value of some of our landscapes—can be costly. We have argued that an increasing awareness of, and access to, standardized dynamic land cover information at a range of spatial and temporal resolutions is giving planners, researchers, and land managers a greater understanding of the scale of observed land cover changes over time, and timely insights as to their causes.

Fundamental to any land cover change application is that the information is fit for the purpose at hand. PMSEIC (1999) noted that decisions about the most appropriate spatial and temporal scales of remote sensing for tackling natural resource problems should be based on scientific information and data—environmental, social, and economic—collected and/or compiled at the relevant scale, e.g., farm, local, catchment, regional, or national levels. Our presentation of the case studies shows that this includes a level of spatial detail that can be used to establish baseline conditions and to detect changes in the area of interest. They also show the importance of evaluating whether these changes are a result of management actions or are changing naturally through environmental processes.

The case studies illustrate that dynamic land cover information has its greatest impact when the full spectrum of complex information—e.g., rainfall deficits, antecedent conditions, ground cover thresholds, landscape context—is reduced to the point where decision-makers are presented with timely, succinct information that supports their decision-making processes.

CONCLUSIONS

Considerable progress has been made over the last decade in understanding the causes and ramifications of human modifications to land cover changes and in tracking trends in ground cover and fire characteristics at increasingly higher spatial and temporal scales. Multi-temporal biophysical archives contribute one piece to this larger picture by helping scientists, decision-makers, and the general public unravel the linkages among the demands from human societies, the effects of modification of the land cover on the functioning of ecosystems, and the delivery of ecosystem services.

Multi-temporal biophysical archives can be expected to continue to improve our ability to model and track the performance of land management interventions as higher resolution imagery archives are developed. In addition, such archives, in combination with other social and economic information, are expected to improve our understanding of the feedbacks from human interactions with the environment and to track the influences of climate change.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/issues/responses.php/5229

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