Paper to IUFRO conference on "*Complex stand structures and associated dynamics: measurement indices and modelling approaches*", Sault Ste Marie, Ontario, Canada, 29 July – 2 August, 2007.

Complex forest stand structures: management, measurement and modelling

Jerome K Vanclay
Southern Cross University
PO Box 157, Lismore NSW 2480, Australia
JVanclay@scu.edu.au

Abstract

A consequence of popular demands for production forestry based on complex stands characterized by vertical, horizontal and spatial heterogeneity is that the estimation and modelling of temporal dynamics and production potential becomes more challenging. New technologies may make it expedient to census remotely and simulate the growth of the whole forest, rather than to rely on the extrapolation from a few precise point samples. Other demands by stakeholders (e.g., for closer attention to plantation water use) create additional challenges that provoke a re-think of traditional approaches to forest inventory and modelling. During the past decade, much effort has been directed at the 'micro-scale', towards better physiological and single-tree models. Changing paradigms of forest management require refinements at the 'meta-scale', to better deal with the complexity created by greater diversity in spatial and temporal structure of forests, and in the demands of stakeholders. The challenge is to create models that are reliable yet accessible and understandable by all stakeholders in the forest management discussion.

Introduction

In setting the stage for an analysis of forest management options in complex stands, it is useful to begin by offering a definition of *complex stands*. This terminology is potentially problematic, as it invites contrary comment (i.e., that all forests are complex, or conversely, that no managed forest is sufficiently complex to reproduce nature), but the terminology is established and widely used. Recent reviews and analyses (McCarthy et al 2004, McElhinny et al 2005, Zenner 2005, Gibbons and Freundenberger 2006, Lindenmayer et al 2006) reveal that existing indices of complexity vary widely in the number and nature of the attributes used, as well as in their utility and application. For this review, a broader generic view is taken by describing complex stands are those characterized by vertical, horizontal and spatial heterogeneity that hampers estimation and modelling of temporal dynamics. This leads to a situation familiar to many tropical foresters: a paucity of data and a plethora of species that may preclude age-based modelling and stratified sampling approaches (Vanclay 1991, 2003a). Modelling approaches used in tropical rainforests (Vanclay 1994) may offer some insights on practical modelling approaches, but the utility of these approaches depends on the local context, so it is important to review both recent developments in forest growth modelling and current imperatives in forest management. Forest growth modelling has blossomed into a large field (Monserud 2003, Gratzer et al 2004, Pinjuv et al 2006, Mendoza and Vanclay 2007), so this review is deliberately biased towards future possibilities in measuring and modelling complex stands, with a special emphasis on Australian forests.

New directions in Forest Management, Measurement and Modelling

Current influences on forest management include (O'Hara 2001, Vanclay 2003b, Larsen and Nielsen 2007):

- less harvesting of old-growth forests, and more harvesting from regrowth stands and industrial plantations;
- less reliance on government forests, and more reliance on private industrial and non-industrial owners;
- fewer vertically-integrated harvesting and processing operations, with lumber increasingly seen as a commodity;
- increasing demands for growers to demonstrate sustainable production, and to gain certification; and
- demands for broader stakeholders representation in planning and overseeing forest operations.

These influences appear to be global and generic, but there are also regional influences. In Europe there are calls for nature-based forest management in both natural and planted stands (Larsen and Nielsen 2007), and in Australia (and many other former European colonies) the thrust is towards the phasing-out of native forest harvesting in favour of plantations (Ajani 2007), preferably with mixtures of indigenous species (Nichols et al 2006). While these views may be prominent, they are not universal, and others hold different views about the role of forests and society.

Some of these influences are contradictory. Figure 1 illustrates some of the mental images that many people may have in mind when they lobby for alternative forest management. This selection of four popular forest images from the internet is undoubtedly biased, because not everyone uses the internet equally, and academics, conservationists and young people are likely to be over-represented amongst the indicators used by Google to rank images. However, these people are also likely to be the most active in lobbying for change in forest management, so any bias is probably inconsequential. These popular images are however, unlikely to be reproduced through nature-based forest management or phasing-out of native forest harvesting, unless there is deliberate intervention to achieve these outcomes (Crow et al 2002, Zenner 2004). So the appropriate response to such pressures may be to invest in education and community consultation.

In parallel with these changes in society and forest management, technological changes also influence modelling endeavours. For decades, modellers have been hampered by technological limitations, and much effort was invested in making models more compact or efficient (Leary 1988). Technological advances mean that most models are now limited by innovation, rather than by computing hardware or software. Comparable progress with remote sensing means that it may soon be more efficient to undertake a forest census using lidar, rather than to sample using ground-based inventory (Lee et al 2004). A forest census obtained efficiently with a remotely-controlled drone would provide geo-referenced height and crown data that could rekindle interest in spatially-explicit models based on height and crown parameters (Busing and Mailly 2004). For decades, yield predictions have been based on small, precise samples, and these point estimates have been scaled up to the stand and estate level. There is little doubt that this remains a good approach for uniform industrial monocultures (but note that agriculture relies increasingly on frequent high-resolution remote-sensing), but the question is whether it remains a useful approach for more complex forests when an alternative – to census and simulate every individual tree – is technologically feasible (Vanclay 2003b). Few error budgets contrasting these alternatives are available to shed light on this issue in complex forests, but the answer is likely to lie in the definition of a 'stand'. If the distribution of trees in a forest is such that stands can be delineated usefully, and that representative samples within those stands can be selected, than the traditional approach will probably continue to suffice. However, complications in identifying stands and representative samples may indicate that it is timely to consider to a new approach. Selected examples are used to illustrate situations in which traditional measurements and models have been unhelpful, and in which a new approach may be more insightful.

Challenges with Plantations

The area of forest plantation in Australia has increased greatly during the last few years, a result of government policies to reduce native forest harvesting and stimulate plantation investment. There are diverse consequences associated with this expansion: community concerns about land use and livelihood changes, about water use by plantations, and about the viability of new plantings on non-traditional sites. Heterogeneity, unfavourable soils and pestilence at these new frontiers have fuelled a discussion about polycultures, and whether they can increase yields and reduce risk to investors (Bristow et al 2006). Simulation studies suggest greater productivity, especially when mixtures include leguminous trees on nitrogen-deficient sites (Forrester at al 2006, Vanclay 2006), but industry has been slow adopt these polycultures (Nichols et al 2006). Clearly, stand-alone simulation studies are not sufficient to initiate uptake, and greater effort is needed to stimulate change.

Much of Australia suffered a seven-year drought during 2000-07, and this has made many communities suspicious of plantations that may use more water than the pasture that they replace (Farley et al 2005). Despite this concern about water and the threat of increased regulation, models of plantation water use tend to be relatively simplistic, and neglect water ‘lost’ to the atmosphere (Watson et al 1997, Makarieva and Gorshkov 2006). Water balance calculations show that much water may be transpired during a few days of arid wind, but relatively little effort has been invested in designs that aerodynamically decouple forest canopies from the atmosphere (Goldberg and Bernhofer 2001, Morse et al 2002). Preliminary results suggest that substantial gains in water-use efficiency can be achieved through deliberate design of the forest canopy (Forrester 2007). Plantation establishment guidelines often prescribe fire- and stream-breaks that fall short of their primary objectives and create turbulence that exacerbates transpiration. More sophisticated ‘wall-to-wall’ spatial modelling may be needed to resolve these crucial issues of water use.

Native Forests and Biodiversity

A popular perception amongst many Australians is that native forests should not be managed deliberately, and that natural processes should prevail to restore forests to their ‘primeval’ state. Sadly, fragmentation means that many natural processes no longer function satisfactorily, and that ‘benign neglect’ may not lead to a good outcome. One example of this is forest decline known as bell miner associated dieback (BMAD) that often occurs when the bell miner, a small but strongly territorial bird, dominates a forest (Wardell-Johnson et al 2006). The proximate cause of decline appears to be an insect (psyllid) outbreak favoured by the territorial behaviour of the bell miners (Stone 2005), but the underlying reason appears related to the vertical structure of the forest, and lidar has been useful for mapping stands at risk of BMAD (Stone and Hayward 2006). Existing forest growth models have been unable to offer useful insights for the management of BMAD, and more sophisticated modelling of stand structure (and possibly of faunal interactions) appears necessary to deal with this issue. Similar questions about the interaction of stand structure and life cycle appear with dwarf mistletoe (Robinson and Geils 2006) and other forest management issues.

The structural diversity of forests is also pivotal in current discussions about faunal biodiversity. Biodiversity has become a topical issue, and stronger regulation of private native forestry is imminent in several Australian states (Vanclay and Nichols 2007). Several uni-dimensional indicators of structural diversity have been proposed (‘biometric’, habitat hectares), but field tests suggest that they are inadequate and that more sophisticated concepts of spatial and temporal variation within forests are needed to advance the discussion surrounding wise forest management in Australia (Jay et al 2007).

People and Forest Dynamics

The shortcoming in the present debate surrounding biodiversity and forest management may be an inadequate understanding and comprehension of forest dynamics. Foresters are trained to think at the landscape-scale, over the long term (Vanclay 2007), but not all nature-lovers share this skill, and opportunities to develop a shared understanding of these insights are often limited. Success stories from Africa attest to the utility of participatory modelling and other systems thinking approaches in helping communities to develop the understanding needed to engage in an informed debate and collectively devise new pathways towards sustainability (Standa-Gunda et al 2003, Vanclay et al 2006). Forest modellers have many of the skills to facilitate such participatory modelling, but one of the challenges is to represent complex processes with simple constructs that are easily communicated. Visual modelling environments such as Simile (Muetzelfeldt and Massheder 2003, Vanclay 2003c) help to make modelling accessible, but inspired leadership is also necessary to guide participants towards models that are both accessible and sufficient.

Future Challenges

During the past decade, much effort has been directed at the 'micro-scale', towards better physiological and single-tree models (Landsberg 2003). Changing paradigms of forest management may stimulate a revival of models at the 'meta-scale', so that we can better deal with the complexity created by greater diversity in spatial and temporal structure of forests, and in the needs and demands of forest managers and stakeholders (Coates et al 2003, Grimm et al 2005, Lischke et al 2006, Scheller and Mladenoff 2007). The biggest challenge is to create models that are reliable yet accessible and understandable by all stakeholders in the forest management discussion. This challenge remains.

References

Ajani, J., 2007. *The Forest Wars*. University of Melbourne Press, Carlton.

Bristow, M., J.D. Nichols and J.K. Vanclay, 2006. Improving productivity in mixed-species plantations. *Forest Ecology and Management* **233**:193-194.

Busing, R.T. and D. Mailly, 2004. Advances in spatial, individual-based modelling of forest dynamics. *Journal of Vegetation Science* 15:831-842.

Coates, K.D., C.D. Canham, M. Beaudet, D.L. Sachs and C. Messier, 2003. Use of a spatially explicit individual-tree model (SORTIE/BC) to explore the implications of patchiness in structurally complex forests. *Forest Ecology and Management* 186:297–310.

Crow, T.R., D.S. Buckley, E.A. Nauertz and J.C. Zasada, 2002. Effects of management on the composition and structure of northern hardwood forests in upper Michigan. *Forest Science* **48**(1):129-145.

Farley, K.A., E.G. Jobbagy and R.B. Jackson, 2005. Effects of afforestation on water yield: a global synthesis with implications for policy. *Global Change Biology* **11**:1565-1576.

Forrester, D.I., 2007. *The Forester* 50(1):20.

Forrester, D.I., J. Bauhus, A. Cowie and J.K. Vanclay, 2006. Mixed-species plantations of *Eucalyptus* with nitrogen fixing trees. *Forest Ecology and Management* **233**:211-230.

Gibbons, P. and D. Freudenberger, 2006. An overview of methods used to assess vegetation condition at the scale of the site. *Ecological Management & Restoration* 7:10-17.

Goldberg, V. and C. Bernhofer, 2001. Quantifying the coupling degree between land surface and the atmospheric boundary layer with the coupled vegetation-atmosphere model HIRVAC. *Annales Geophysicae* **19**:581–587.

Gratzer G., C. Canham, U. Dieckmann, A. Fischer, Y. Iwasa, R. Law, M.J. Lexer, H. Sandmann, T.A. Spies, B.E. Splechtna and J. Szwagrzyk, 2004. Spatio-temporal development of forests - current trends in field methods and models. *Oikos* **107**:3-15.

Grimm,V., E. Revilla, U. Berger, F. Jeltsch, W.M. Mooij, S.F. Railsback, H.-H. Thulke, J. Weiner, T. Wiegand and D.L. DeAngelis, 2005. Pattern-Oriented Modeling of Agent-Based Complex Systems: Lessons from Ecology. *Science* 310:987-991.

Jay, V.A., J.D. Nichols and J.K. Vanclay, 2007. Social and ecological issues for private native forestry in northeastern New South Wales, Australia. *Small-scale Forestry* **6**(2):115-126.

Landsberg, J., 2003. Physiology in forest models: History and the future. *FBMIS* 1:49-63.

Larsen, J.B. and A.B. Nielsen, 2007. Nature-based forest management - Where are we going? *Forest Ecology and Management* 238:107-117.

Leary, R.A., 1988. Some factors that will affect the next generation of forest growth models. *In:* A.R. Ek, S.R. Shifley and T.E. Burk (eds) Forest Growth Modelling and Prediction. Proceedings of IUFRO Conference, August 23-27, 1987, Minneapolis, Minnesota. USDA Forest Service General Technical Report NC-120, p. 22-32.

Lee, A., R. Lucas and C. Brack, 2004. Quantifiying vertical forest stand structure using small footprint lidar to assess potential stand dynamics. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences* 36(8):213-217.

Lindenmayer, D.B., J.F. Franklin and J. Fischer, 2006. General management principles and a checklist of strategies to guide forest biodiversity conservation. *Biological Conservation* **131**:433–445.

Lischke, H., N.E. Zimmermann, J. Bolliger, S. Rickebusch and T.J. Löffler, 2006. TreeMig: A forest-landscape model for simulating spatio-temporal patterns from stand to landscape scale. *Ecological Modelling* 199:409–420.

Makarieva, A.M. and V.G. Gorshkov, 2006. Biotic pump of atmospheric moisture as driver of the hydrological cycle on land. *Hydrology and Earth System Sciences Discussions* 3:2621–2673.

McCarthy, M.A., K.M. Parris, R. van der Ree, M.J. McDonnell, M.A. Burgman, N.S.G. Williams, N. McLean, M.J. Harper, R. Meyer, A. Hahs and T. Coates, 2004. The habitat hectares approach to vegetation assessment: An evaluation and suggestions for improvement. *Ecological Management & Restoration* **5**(1):24-27.

McElhinny, C., P. Gibbons, C. Brack and J. Bauhus, 2005. Forest and woodland stand structural complexity: Its definition and measurement. *Forest Ecology and Management* 218:1-24.

Mendoza, G.A. and J.K. Vanclay, 2007. Trends in forestry modelling. *Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources*, in press.

Monserud, R.A., 2003. Evaluating forest models in a sustainable forest management context. *Forest Biometry, Modelling and Information Sciences* 1:35-47.

Morse, A.P., B.A. Gardiner and B.J. Marshall, 2002. Mechanisms controlling turbulence development across a forest edge. *Boundary-Layer Meteorology* 103:227–251.

Muetzelfeldt, R. and Massheder, J., 2003. The Simile visual modelling environment. *European Journal of Agronomy* 18(3–4):345–358.

Nichols, J.D., M. Bristow and J.K. Vanclay, 2006. Mixed species plantations: prospects and challenges. *Forest Ecology and Management* **233**:383-390.

O'Hara, K.L., 2001. The silviculture of transformation – a commentary. *Forest Ecology and Management* 151:81-86.

Pinjuv, G., Mason, E.G. and Watt, M., 2006. Quantitative validation and comparison of a range of forest growth model types. *Forest Ecology and Management* 236: 37–46.

Robinson,D.C.E. and B.W. Geils, 2006. Modelling dwarf mistletoe at three scales: life history, ballistics and contagion. *Ecological Modelling* **199**:23–38.

Scheller, R.M. and D.J. Mladenoff, 2007. An ecological classification of forest landscape simulation models: tools and strategies for understanding broad-scale forested ecosystems. *Landscape Ecology* **22**:491–505.

Stone, C., 2005. Bell miner associated dieback at the tree crown scale: A multitrophic process. *Australian Forestry* (Dec 2005).

Standa-Gunda, W., T. Mutimukuru, R. Nyirenda, R. Prabhu, M. Haggith and J.K. Vanclay, 2003. Participatory modelling to enhance social learning, collective action and mobilization among users of the Mafungautsi Forest, Zimbabwe. *Small-scale Forestry* **2**(2):313-326.

Stone, C. and A. Haywood, 2006. Assessing canopy health of native eucalypt forests. *Ecological Management & Restoration* 7(1):24-30. doi:10.1111/j1442-8903.2006.00288.x

Vanclay, J.K., 1991. Data requirements for developing growth models for tropical moist forests. *Commonwealth Forestry Review* **70**:248-271.

Vanclay, J.K., 1994. *Modelling Forest Growth and Yield: Applications to Mixed Tropical Forests*. CAB International, Wallingford.

Vanclay, J.K., 2003a. Growth modelling and yield prediction for sustainable forest management. *The Malaysian Forester* **66**(1):58-69.

Vanclay, J.K., 2003b. Realizing opportunities in forest growth modelling. *Canadian Journal of Forest Research* **33**(3): 536-541.

Vanclay, J.K., 2003c. The One-minute Modeller: An Introduction to Simile. *Annals of Tropical Research* **25**(1):31-44.

Vanclay, J.K., 2006. Spatially-explicit competition indices and the analysis of mixed-species plantings with the Simile modelling environment. *Forest Ecology and Management* **233**:295-302.

Vanclay, J.K., 2007. Educating Australian foresters for the 21st century. *International Forestry Review*, in press.

Vanclay, J.K. and J.D. Nichols, 2007. A long and winding road: the regulation of private native forestry in New South Wales, Australia. *Small-scale Forestry* **6**(2):111-113

Vanclay, J.K., R. Prabhu and F.L. Sinclair, 2006. *Realizing Community Futures: A practical guide to harnessing natural resources*. Earthscan, London.

Wardell-Johnson, G., C. Stone, H. Recher and A.J.J. Lynch, 2006. A review of eucalypt dieback associated with Bell miner habitat in north-eastern New South Wales, Australia. DEC NSW Occasional Paper DEC 2006/116.

Watson, F.G.R., R.A. Vertessy, R.B. Grayson, L.E. Band and T.A. McMahon, 1997. Macaque: regional scale modelling of water yield from forested basins. *Water* **24**(1):10.

Zenner, E.K., 2004. Does old-growth condition imply high live-tree structural complexity? *Forest Ecology and Management* **195**:243–258.

Zenner, E.K., 2005. Investigating scale-dependent stand heterogeneity with structure-area-curves. *Forest Ecology and Management* **209**:87-100.

Figure 1. Four of the 18 most popular forest images on the internet, retrieved by searching for ‘forest’ with Google Images in July 2007.