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The Sustainable Grazing Systems National Experiment. 1. Introduction and methods

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Abstract. This paper outlines the development and design of the Sustainable Grazing Systems (SGS) National Experiment from the initial call for expressions of interest, through several workshop processes to the final selection and implementation of its 6 component sites, and the general methodology used at each. Sites were located in Western Australia, western Victoria, north-east Victoria, and on the Central Tablelands, North West Slopes, and the eastern Riverina of New South Wales. Sites in Western Australia, north-east Victoria, the North West Slopes, and the eastern Riverina also had subsites. Methods for the sites and subsites (data collection for pastures, livestock, weather, soils and site characterisation) are presented to provide a central reference, and to save duplication in subsequent papers. Descriptions are provided of the location, average annual rainfall, major pasture, soil and stock types, design and number of treatments, and initial soil levels (0–10 cm) of phosphorus, electrical conductivity, and pH for sites and subsites. Also outlined is the major focus of the research undertaken at each site. While sites studied regionally relevant issues, they operated under a common protocol for data collection with a minimum data set being specified for each of 5 unifying themes: pastures, animal production, water, nutrients, and biodiversity. Economic analyses were also undertaken at the macro- and micro-level, and a procedural tool developed for appraising the on- and off-farm impacts of different systems. To give effect to the themes, common database and modelling tools were developed specifically for the national experiment, so that collectively sites comprised a single experiment.

Introduction

The Sustainable Grazing Systems (SGS) Program was comprised of 4 major subprograms (Mason *et al*. 2003*a*): the national experiment, regional producer network (Simpson *et al*. 2003), PROGRAZE (Bell and Allan 2000), and the overall project management. This paper provides a comprehensive description of the national experiment as a background to the site and theme papers in this special issue. It also outlines the rationale for the national experiment and how it developed, and reflects on its role as a 'new' model for agricultural research and development (R&D). Site descriptions and locations are included along with an overview of the main data collection techniques used by the sites and themes, and the role of themes, the database (Scott and Lord 2003) and SGS pasture model (Johnson *et al*. 2003). A further paper (Andrew *et al*. 2003) reports the scientific outcomes from the sites and themes, and explores the effectiveness of key elements used in the R&D process.

Goal and objectives

The overarching goal of the national experiment was to fill the gaps in knowledge relating to the major profitability and sustainability issues in high rainfall zone (HRZ, annual rainfall >600 mm) grazing systems in southern Australia, create new knowledge and insights into the mechanisms and processes involved in grazing systems, and to create an enriching environment for researchers and producers alike. It aimed to: (i) quantify the relationships between management options, and production and sustainability outcomes across a range of grazing systems; (ii) develop grazing systems that were more sustainable and at least 10% more profitable than current practice; (iii) facilitate rapid delivery of the research results to producers through the regional producer network; and (iv) develop a more effective model for conducting large-scale, industry-focused research.

Specific objectives of the national experiment were to: (i) demonstrate that grazing management can increase pasture productivity and sustainability by increasing the proportion of perennial grasses and increasing persistence; (ii) determine the profitability of grazing strategies within sustainable parameters; (iii) determine the management needed to provide critical ground cover to prevent erosion and promote soil health; (iv) develop strategies that maximise water use and minimise salinity and acidity; (v) identify strategies that optimise animal production and reduce nutrient losses; and (vi) determine the impact of grazing systems and management intensifications on biodiversity.

In SGS, a 'sustainable grazing system' referred to a process of continuous improvement that balanced the following 6 general requirements (Mason *et al*. 2003*a*) and

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prioritised them for an individual property: (i) increasing grazing system productivity and profitability; (ii) increasing water use in the grazing system; (iii) protecting the on-farm natural resources; (iv) creating more opportunities for biodiversity; (v) reducing off-site impacts from the grazing system; and (vi) improving producer satisfaction, motivation and capacity to implement change.

The national experiment comprised an integrated network of 6 national research sites across the southern HRZ from Albany in Western Australia to Tamworth on the north-west slopes of New South Wales (Fig. 1), linked by 5 themes (water, nutrients, pastures, animal production, and biodiversity) and economic analyses based on a common set of measurements across the sites. Individual site and subsite results were presented in papers by Chapman *et al*. (2003), Garden *et al*. (2003), Johnston *et al*. (2003), Lodge *et al*. (2003*a*, 2003*b*, 2003*c*), McDowall *et al*. (2003), Michalk *et al*. (2003), Ridley *et al*. (2003) and Sanford *et al*. (2003*b*), and the outcomes of the themes reported for water by White *et al*. (2003), pastures (Sanford *et al*. 2003*a*), animal production (Graham *et al*. 2003), nutrients (McCaskill *et al*. 2003) and biodiversity (Kemp *et al*. 2003). Individual site and theme papers detail any variations to the data collection methods outlined in this paper. A common database (Scott and Lord 2003) and the purpose-built SGS Pasture Model (Johnson *et al*. 2003) enabled sites and themes to be linked into the common hypothesis 'that management practices can improve the profitability and sustainability of grazing systems in the HRZ of southern Australia'. A net cash flow–sustainability analysis tool was also developed to assess the national experiment treatments in an integrated way (Barlow *et al*. 2003).

Designing and implementing the national experiment

Design of the national experiment incorporated both the need for new outcomes in sustainable grazing systems, and for a new R&D process to effectively demonstrate environmental stewardship, make real progress towards addressing the major environmental threats facing the grazing industry (increasing dryland salinity and soil acidity, and declining biodiversity), and incorporate higher water-demanding plants, including perennial grasses. There was also a strong recognition of the need to solve the problem, rather than just study it; and to co-partner with producers in a meaningful way that ensured relevance and uptake of the findings by developing a fresh approach to R&D. Often conventional approaches have failed to translate investor inputs (both funding and research effort) into changes on-farm efficiently or effectively (Carberry 2001).

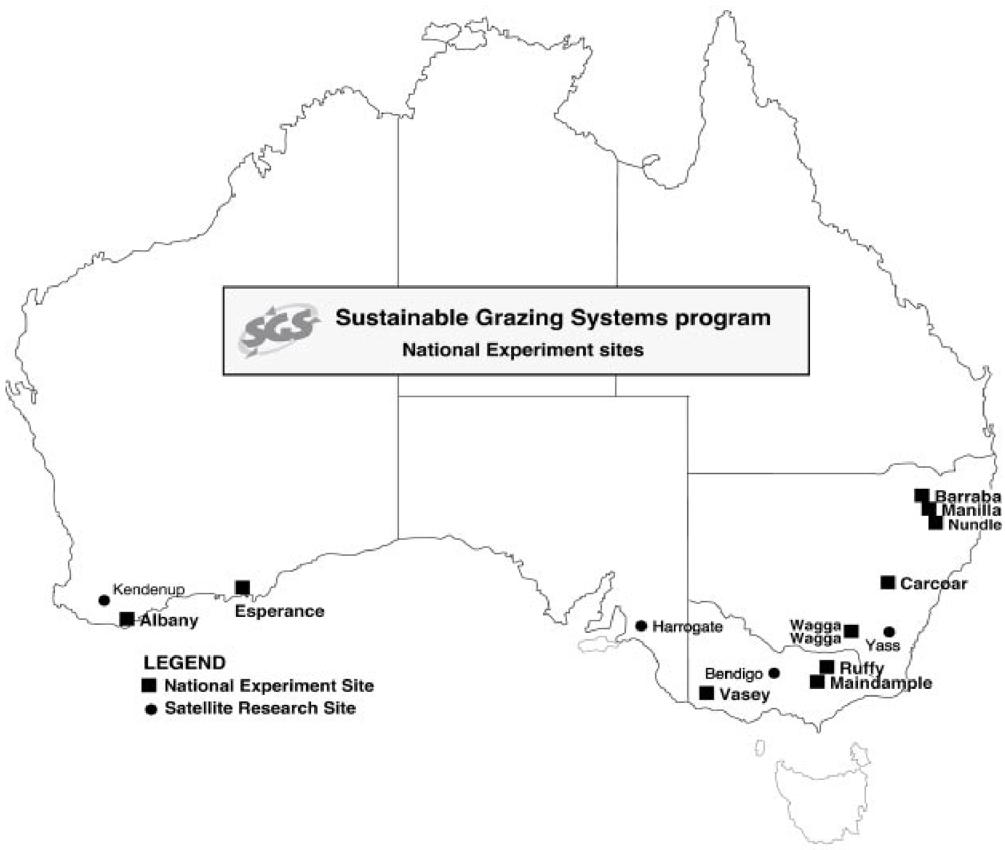

Figure 1. Location of national experiment sites in the high rainfall zone of southern Australia.

Table 1. Differences between traditional and systems-oriented research (from Johnson *et al*. 2001)

'Traditional' experimental approach (i.e. seeking differences among treatments)	Systems-oriented methodology
Fewer well-controlled treatments	Treatments broadly defined, many factors uncontrolled, deals with complexity and natural variability
Replicated	May not be replicated in the 1 location
Controlled experimental conditions and treatments, few interactions	Only partial control over conditions and treatments, many interactions
Small scale	Can range in scale, typically natural units of management unit size e.g. catchment, paddock
Constrained to small plots, replicated	Real world
Amenable to statistical analysis	Typically interpreted using a physically based model, or rely on large sample survey, using regression analysis
Scale chosen to limit variability	Many processes operate in the real world at scales that cannot be sensibly replicated

To effectively address the issue of declining pasture productivity and sustainability in grazing systems of the HRZ of southern Australia, this new approach, adopted for the national experiment, integrated sustainability and production research into a single program, not separately as for phase 1 (Temperate Pastures Sustainability Key Program, Mason *et al*. 2003*a*). In doing this, other issues also needed to be considered, such as incorporating a range of pasture, soil and land types and credibly extrapolating findings beyond the site locations. Modelling was a critical component to help achieve this. Above all, this required having a national research focus that used a multi-disciplinary team approach to conduct research at a meaningful scale to mimic real production systems, and incorporated both bottom-up (local) and top-down (national) imperatives. To meet these requirements, the national experiment therefore included elements of a systems approach, as summarised (Table 1) by Johnson *et al*. (2001).

One of the foundations for the successes of the national experiment was the process used to develop it, which incorporated many elements different from a traditional R&D approach (Andrew *et al*. 2003). SGS began with a call for expressions of interest for groups to be involved in the collective development of the program, rather than inviting site research proposals *per se*. The SGS program coordinator and theme coordinator then visited potential groups to market and explain the new program. From the 22 expressions of interest received, 5 groups were selected on the basis of their perceived ability to participate in this new interactive program. At a meeting in which these groups were selected, the funding providers also listed 13 achievements (Table 2) that they anticipated would be achieved by the SGS National Experiment Program. While some of the proposed program features did not subsequently occur (e.g. monitor farms), this list showed that the funders had a high expectation of what the SGS National Experiment could achieve.

In addition, a pre-existing Murray–Darling Basin Commission (MDBC)-funded research group based at Wagga Wagga in the eastern Riverina of New South Wales joined the SGS National Experiment. Funding for a notional sixth research group was kept aside to support the (initially unspecified) across-site activities. Site leaders workshopped early-draft site research plans in October 1996. Site teams then held research planning meetings facilitated by the theme or SGS coordinator, culminating in a major research workshop in December 1996 attended by 55 people [researchers, experts in modelling, hydrology and statistics, producer members of the SGS steering group (Mason *et al*. 2003*a*), and staff of Meat & Livestock Australia and Land & Water Australia, the major funders]. This workshop was a watershed for the national experiment, in that it recognised: (i) the importance of undertaking pre-experimental modelling to examine the likely effectiveness of treatments to control the water cycle. CSIRO Land and Water was commissioned to undertake this work (Bond *et al*. 1997); (ii) the importance of taking a catchment approach where possible, leading to a planning workshop on catchment hydrology (held March 1997) and to a catchment-based research design at the north-east Victoria site. The MDBC-funded site in the eastern Riverina was also catchment-based; (iii) the need to develop common themes to link across-sites, which led to the formation of theme teams; (iv) the role of modelling as a key tool to achieve the across-site integration. This led to a modelling workshop (held May 1997) to explore a range of options, culminating in the development of the SGS pasture model (Johnson *et al*. 2003); (v) the importance of biodiversity for the national experiment as a component of sustainability, leading to a biodiversity research planning workshop held February 1997; (vi) the integral and valuable role of producers in R&D, with steering group producers facilitating theme discussion groups.

Furthermore, these workshop processes helped to build a national experiment community. The national experiment was coordinated jointly by the theme coordinator and the SGS program coordinator, who worked closely with site leaders, theme convenors, the modeller and the database

Table 2. Anticipated achievements of the national experiment as outlined by the SGS funders at a meeting to select the site teams

Expectations were formulated in discussion at the meeting held on 19 September 1996, and are a valuable record of the achievements expected by the funding organisations.

1	Know how sustainable present management practices are, what practices are likely to be sustainable; and provide useable sustainability indicators
2	Much greater insights, indeed knowledge, of the processes underlying the SGS research issues
3	Specifically, greater insights into the role of grazing management options in mediating the effectiveness of perennial pastures for increasing water use; and the real effect this has in minimising off-site effects
4	Quantified the trade-offs between production and sustainability [e.g. high-input systems (off-site impacts), low-input systems (on-site mining of resources)]
5	Much greater confidence about the role, place, value and effectiveness of trees in sustainable grazing systems
6	Successfully extrapolated the research results from plots to paddocks, whole farms, landscapes and catchments, via modelling
7	Confidence in the findings because of the links with the co-learning sites and monitor farms, and sound modelling
8	Assisted producers to determine which kinds of grazing management strategies are appropriate for them, through the provision of this 'extrapolated' information
9	Significant progress towards industry benchmarks for best management practice in terms of sustainability, and using land according to its capability
10	Developed tools for producers to decide if they are achieving production and sustainability targets
11	Confident of findings given that research, development and extension (R, D&E) work occurred in parallel
12	The SGS process viewed as a successful model for how to conduct R, D&E
13	A network of researchers interested in sustainability and production issues which, through interaction within the SGS and other programs, can sharpen the focus of such research in Australia

specialist. Collectively these formed the national experiment research executive.

National research sites

Of the 6 national experiment sites across southern Australia, 3 were in New South Wales (North West Slopes, Central Tablelands and eastern Riverina), 2 in Victoria (north-east Victoria and western Victoria) and 1 in Western Australia. Several 'sites' were comprised of subsites with different experiments (Western Australia), or different locations of the same basic design (north-east Victoria; eastern Riverina and North West Slopes; Fig. 1, Table 3). When referring to separate research locations in this paper, the term 'sites' includes 'subsites'. Further site details are in Table 4 (location, elevation, soil type, rainfall and stock type). Collectively, sites covered a range of pasture and soil types (Tables 3 and 4) and soil fertility levels (Table 5).

In the national experiment, the following definitions were used for the different pasture types: native pasture — a pasture comprising >90% indigenous species; naturalised pasture — a pasture with a high proportion but <90% of native species; volunteer pasture — a pasture containing predominantly self-sown exotic species; and sown pasture — a pasture with predominantly sown exotic cultivars.

Each site comprised a unique, self-contained experiment(s) focused on the priority issues for that site and the local region (Table 3) that could be analysed and reported without reference to the other national experiment sites. Sites collected a minimum data set (Lodge 1998) for each of the 5 integrating themes, so that collectively sites also comprised a single, national experiment. Common features across the national experiment sites were that sheep were the grazing animal (except for beef cattle at Esperance), and sites were located on commercial properties, not research facilities (except for the eastern Riverina site). Phalaris (*Phalaris aquatica* L.) was the most commonly used exotic perennial grass. Various grazing manipulations were used as experimental treatments. In the national experiment, 'grazing management' was a term used broadly (see Morley 1966) as the control of pastures and livestock and their movements in a pasture ecosystem. This embraced the control of the pattern of stock movements or grazing strategy and methods, pasture management or control of species, fertility, agronomic practices, animal management, stock type and enterprise mixes.

Research plans at some sites were modified to accommodate the findings of the pre-experimental modelling. This showed that perennial bunch-grass [such as phalaris and cocksfoot (*Dactylis glomerata* L.)] pastures were likely to be too shallow-rooted and too inactive in winter to substantially reduce drainage of soil water below the rooting depth across most of the national experiment (Bond *et al*. 1997), and made the case for including deep-rooted species of different phenology into the national experiment design. Accordingly, trees were incorporated into the experimental designs at Albany (blue gum woodlots), and Maindample and Vasey (isolated, remnant mature eucalypts).

Materials and methods

Data collection in the national experiment

All data were collected according to a pre-determined experimental protocol (Lodge 1998) that applied to all sites in the national experiment. This protocol, developed collectively by the national experiment researchers, detailed methods of measurement, standardised sampling procedures for data collection, sample numbers and sampling frequency, as well as analytical methods and units of measurement.

Although methods and procedures were detailed in the protocol (Lodge 1998), a brief description is provided here for completeness. Descriptions of data collection procedures have been presented for pastures (Sanford *et al*. 1998), animal production (Graham and Borg 1998), water (White and Ridley 1998), nutrients (McCaskill 1998) and biodiversity (Kemp 1998). Variations to the standard protocols and further details of experimental methods were provided in individual papers for sites and subsites at Albany (Sanford *et al*. 2003*b*), Esperance (McDowall *et al*. 2003), Vasey (Chapman *et al*. 2003), north-east Victoria (Ridley *et al*. 2003), eastern Riverina (Johnston *et al*. 2003), Yass (Garden *et al*. 2003), Carcoar (Michalk *et al*. 2003), and Barraba and Manilla (Lodge *et al*. 2003*a*, 2003*b*). Experimental details and results for the Nundle site (phalaris–subterranean clover) on the North West Slopes of New South Wales have been reported previously (Lodge and Murphy 2001; Lodge *et al*. 2003*c*).

Species composition, *percent green*, *total herbage mass and litter mass*. Species composition (as a percentage of total herbage mass) was estimated using BOTANAL procedures (Tothill *et al*. 1992) that combined a dry-weight rank method (Mannetje and Haydock 1963) with an estimate of total herbage mass (Hodgson 1979) — commonly obtained using the comparative yield method of Haydock and Shaw (1975). For the dry-weight rank estimates, tied ranks and modifications to the multipliers for cumulative ranks (Jones and Hargreaves 1979), were applied.

Total herbage mass was estimated using the comparative yield technique at all sites except north-east Victoria, Vasey and eastern Riverina. For north-east Victoria and Vasey, total herbage mass was estimated using a weighted disk method (Cayley and Bird 1991). At the eastern Riverina site an electronic pasture probe (a Mosaic Systems single probe

Table 3. Sites, designs and numbers of treatments and the major focus of each site in the SGS National Experiment

Region/sites	Subsites	Pasture type	Design	No. of treatments	Major focus
North West Slopes, NSW	Barraba Manilla Nundle	Native Native Phalaris/sub. clover	Replicated plots	5 5 4	Assessment of the importance of ground cover, runoff, soil and nutrient loss, water infiltration, soil microbial activity and carbon cycling, and how these interact with productivity and profitability
Central Tablelands, NSW	Carcoar	Naturalised, sown and chicory	Replicated plots	7	Comparison of a range of strategies, from low to high input (physical as well as managerial) to allow assessment of the productivity, profitability and sustainability of each option, and the impact of intensification of pasture systems on biodiversity; incorporates a lamb production and finishing system to produce large lambs out-of-season
Eastern Riverina	Wagga Wagga	Native and phalaris	Unreplicated catchments	1	Examination of the extent to which native grass pastures in the Murray–Darling Basin can be managed for improved profitability and sustainability; the key focus is water use to reduce groundwater recharge
Eastern Riverina satellites	Bendigo, Harrogate, Yass	Naturalised and native	Replicated	4, 5 and 6	Determination of the extent to which native and naturalised pastures can be managed for improved profitability and sustainability
North-east Victoria	Maindample	Annual/phalaris/sub. clover.	Unreplicated catchments	3	Measurement of the catchment scale water and nutrient movement with low, medium, or high inputs
	Ruffy	Annual/cocksfoot/sub. clover			
Western Victoria	Vasey	Naturalised, phalaris/sub. clover	Replicated plots	9	Optimisation of water use and animal production by managing interactions between grazing management, nutrient use, green leaf production, water use and animal nutritional requirements; incorporates a lamb finishing system
Western Australia	Albany	Tree/kikuyu/sub. clover	Replicated plots	6	Assessment of the role of perennial pastures to increase profits and water use and trees in grazing systems
	Kendenup	Kikuyu/sub. clover	Unreplicated	2	Determination of the extent to which a summer active perennial grass can reduce groundwater recharge in a <600 mm annual rainfall environment
	Esperance	Kikuyu/sub. clover	Unreplicated	3	Comparison between beef production systems on annual or perennial pastures

electronic capacitance meter) and quadrat harvesting were used to estimate total herbage mass.

For each sampling time, total herbage mass, along with the proportion (% of total) or actual amounts (kg DM/ha) of green material, litter mass (eastern Riverina and north-west slopes sites only) and ground cover (all sites except Albany, Esperance and Vasey), were estimated in 10–30 calibration quadrats. To ensure that the calibration quadrats represented the range of estimates, a proportion (20–35%) was selected near the upper and lower limits. All samples were transported and stored in cooled storage units before processing. Freshly harvested material was hand-sorted into green and dead portions and these components were oven-dried at 80°C for 48 h, before being used to calculate percent green and summed for total herbage mass.

Regression was used to determine the relationship between actual and estimated values from the calibration quadrats for total herbage, litter mass and percent green. Regression curve fitting procedures were restricted to either linear or quadratic regressions, since these were more appropriate for the data (Tothill *et al*. 1992) and generally had the highest R^2 values. These derived regression equations were used to predict herbage mass, percent or amount of green and litter mass where appropriate. Dry weight-rank estimates were converted to the percentage that each species contributed to total herbage mass using the algorithms, multipliers and procedures described by Mannetje and Haydock (1963), Jones and Hargreaves (1979) and Tothill *et al*. (1992). These values were expressed as percent composition and used to calculate the herbage mass (percent composition multiplied by total herbage mass, kg DM/ha) of each species. Similar procedures were used for herbage mass estimates obtained by the weighted disk (north-east Victoria and Vasey sites) and electronic pasture probe (eastern Riverina site). Details of the methods used to obtain and calculate herbage accumulation (Hodgson 1979) data at each of the sites were reported by Sanford *et al*. (2003*a*). Ground cover estimates were taken using the procedures described by Murphy and Lodge (2002).

In addition to the normal BOTANAL sampling, the presence of all species in each sampling quadrat was also recorded in autumn and spring each year, and also the presence of any other species that occurred in the paddock but was not detected in any quadrat.

Table 4. Latitude, longitude, elevation (m), long-term average annual rainfall of closest town (mm), main soil types and stock types for each of the national experiment sites

Region, site and subsite	Nearest major centre	Latitude	Longitude	Elevation (m)	Annual rainfall (mm)	Main soil type(s)	Stock type
			North West Slopes, NSW				
Barraba	Tamworth	30°34′S	150°38′E	510	694	Red chromosol	Merino wethers
Manilla	Tamworth	30°49′S	150°42′E	475	654	Red chromosol/brown vertosol	Merino wethers
Nundle	Tamworth	31°24′S	151°07′E	590	834	Brown chromosol/brown sodosol	Merino wethers
			Central Tablelands, NSW				
Carcoar	Orange	33°35′S	149°10′E	830	935	Brown chromosol/brown kurosol	Prime lambs
			Eastern Riverina, NSW				
Wagga Wagga	Wagga Wagga	35°07′S	147°18'E	222	574	Red chromosol/leptic tenosol	Merino wethers
			Southern Tablelands, NSW				
Yass (Wagga Wagga subsite)	Canberra	34°40′S	148°52′E	670	646	Yellow sodosol/hydrosol	Merino wethers
			Central Victoria				
Bendigo (Wagga Wagga subsite)	Bendigo	37°0′S	144° 22′E	315	643	Yellow kerosol	Merino wethers
			Mt Lofty Ranges, SA				
Harrogate (Wagga Wagga subsite)	Adelaide	34°55′S	139°02′E	370	556	Bleached mottled red chromosol	Merino wethers
			North-east Victoria				
Maindample	Benalla	36°59′S	145°59′E	350	719	Brown sodosol	Prime lambs
Ruffy	Benalla	37°00′S	145°27′E	400	804	Brown kurosol	Merino ewes
			Western Victoria				
Vasey	Hamilton	37°24′S	141°55′E	261	625	Yellow sodosol	Merino ewes
			Western Australia				
Albany	Albany	34°54′S	117°49′E	60	810	Petroferric brown sodosol	Merino wethers
Kendenup	Mt Barker	34°32′S	117°33′E	270	550	Ferric mesotrophic brown chromosol	Merino wethers
Esperance	Esperance	33°41′S	121°52′E	142	563	Subnatric sodosol	Hereford cows

Livestock production. Livestock were provided by the co-operating landholders at all sites, except Carcoar. All sites were stocked with sheep, except Esperance which was stocked with Hereford cows and calves. Husbandry practices (crutching, shearing etc.) were carried out by landholders or technical staff associated with each site. For wethers, liveweights and condition scores were determined at least at the start and end of each season. For ewes, liveweight and

Table 5. Initial P levels (Bray No. 1, Colwell and Olsen; 0–10 cm), EC, soil pH (1:5 water and 1:5 $CaCl_2$) and fertiliser applied at each of the SGS National Experiment sites

Treatment	P (mg P/kg) Bray	Colwell	Olsen	EC	pH (water)	pH ($CaCl_2$)	Fertiliser[A]	P application rate (kg P/ha.year) 1997	1998	1999	2000	2001
					Barraba							
Unfertilised	32	61	32.4	0.07	6.9	6.2	SSP + SF	0	0	0	0	0
Fertilised								11	11	0	11	0
					Manilla							
Unfertilised	12	26	12.0	0.06	6.6	5.9	SSP	0	0	0	0	0
Fertilised								11	11	0	22	0
					Nundle							
All	12.2	24	10.8	0.06	5.7	4.9	SSP	17.6	11	11		
					Carcoar							
Unfertilised unsown control (continuous)	9	20	5.7	0.14	5.9	4.9	Nil	0	0	0	0	0
Fertilised sown (sown flexible)	11.0	19.7	8.0	0.1	6.0	5.4	SSP + lime[G]	22.5	9.8	22.5[B]	0	0
					Wagga Wagga							
Native	4.3	6	3	0.07	5.5	4.7	SSP and SF	8.8		13.2		10.82
Phalaris	24	30	13	0.12	5.2	4.8	SSP	22	15.84		22	22.62
					Yass							
No input	5.1	6	—	0.04	—	4.3		N/A	0	0	0	0
Moderate input	5.6	6.6	—	0.04	—	4.1	SSP	N/A	11[C]	11	11	11
					Maindample							
Control	11	26	11	0.08	4.9	4.2	SSP	5.5	5.5	5.5	5.5	5.5
Medium	18	31	13	0.09	5.5	4.6	SSP + lime[G]	11	11	11[D]	11	11
High	24	45	18	0.1	5.8	4.9	SSP + lime[G]	22	22	22[D]	22	22
					Ruffy							
Control	11	20	9	0.07	5.2	4.4	SSP	4.5	4.5	4.5	4.5	4.5
Medium	18	30	12	0.1	5.3	4.5	SSP	9	9	9	9	9
High	39	86	22	0.13	5.6	4.9	SSP	27	27	27	27	27
					Vasey[E]							
Low — volunteer pasture	4.6	12	5	0.06	5.5	4.7	SSP	8	8	8	8	8
Medium — sown pasture	12	27	8.0	0.08	5.5	4.8	SSP	8	8	8	0	8
High — sown pasture	12	30	8.6	0.08	5.5	4.7	SSP + DSP	30	50[F]	25	10	10
					Esperance							
Annual	11	9	6	0.09	5.6	4.9	SSP	9	9	9	9	9
Kikuyu	16	16	10	0.09	5.7	5.0	SSP	9	9	9	9	9
					Albany							
Annual	37	40	20.0	0.15	5.8	4.9			12.32	12.32	12.32	
Kikuyu	37	51	23.0	0.23	6	5.4			12.32	12.32	12.32	
					Kendenup							
Annual		30		0.21	5.6	4.9	SSP		11.44	11.44	11.44	
Kikuyu		38		0.28	5.3	4.8	SSP		11.44	11.44	11.44	

[A]SSP, single superphosphate or Superfect (8.8% P, 11% S); DSP, double superphosphate (16.8% P, 4% S); SF, sulfur-fortified super (8% P, 25% S); Granulok, 14% N, 11.5% P, 10% S.
[B]SSP-Mo, 8.8% P, 11% S, 0.05% Mo. [C]Mo (25 g/ha) as molybdenised superphosphate in 1998. [D]K in potash lime applied at 2.5 t/ha in 1999.
[E]Soil samples collected in June 1997 before fertiliser application. [F]Potassium added (30 kg K/ha) as KCl in 1998.
[G]Lime applied 2.5 t/ha: Carcoar — 1997; and Maindample — high and medium 1999, high 1992, and medium 1996.

condition scores were taken 6 weeks pre-joining, at joining, mid-pregnancy, pre-lambing, at marking and weaning, and at the change of each season. Animals were weighed at about the same time of day on each occasion, without overnight fasting. Condition of sheep was assessed by feeling the backbone and lumbar processes with the fingers (Jefferies 1961) and scored as: score 1, very lean, poor store condition; score 2, lean, average store condition; score 3, medium, forward store condition; score 4, fat; and score 5, very fat. Lamb numbers and liveweight were recorded at marking and weaning. Either a full live animal assessment or carcass assessment was undertaken for weaner progeny. Stocking rate at each site was expressed as a dry sheep equivalent (DSE), relative to a 45 kg wether (DSE = 1) (a 50 kg Merino wether was used as 1 DSE at the Carcoar site) using the criteria described in the PROGRAZE manual (Anon. 1995).

At shearing, fleece weight (fleece and belly wool) was recorded and a mid-side sample taken for determination of fibre diameter (μm), clean wool yield (as a percentage of greasy wool weight), staple length (mm), staple strength (N/kilotex), and point-of-break (tenderness). These data were used to estimate the value of wool (cents/kg) for each treatment.

Procedures for weighing and condition scoring cows and calves at the Esperance site were described by McDowall *et al*. (2003).

Weather data. Each site maintained an automatic weather recording station. Rainfall (mm) was measured in tipping bucket pluviometers at intervals of 30–60 min, backed up by manual rain gauges (1–9 per site) or additional pluviometers. Rainfall data for each site over the period of data collection are summarised in Table 6.

Ambient temperature (daily maximum, minimum and mean, °C), solar radiation (W/m^2, converted to MJ/m^2.day), relative humidity (%) and wind speed (km/day) were collected at time intervals of 30–60 min. These data were used to calculate reference (potential) evapotranspiration (ET_{ref}, mm), using the Penman–Monteith combination equation (Smith 1992) and Priestley–Taylor equation (Priestley and Taylor 1972). For all sites a standard canopy reflection coefficient (α = 0.23) was used. At Albany, Esperance, Vasey, Carcoar, and the north-east Victoria sites net radiation was measured directly; for all other sites it was calculated from measurements of solar radiation, mean daily relative humidity and daily maximum and minimum temperatures, using the procedures of Smith (1992). Soil heat flux plates were installed at Albany, Carcoar and the north-east Victoria sites and recorded variously at 1–60 min intervals. Otherwise, daily soil heat flux was calculated as 0.38 × (average air temperature day_n – average air temperature day_{n-1}).

Soil water content. Neutron moisture meter (NMM) access tubes were installed at all sites to depths ranging from 140 to 210 cm, except at Albany where some tubes were installed to a depth of 575 cm. Readings were taken approximately every 4 weeks, except in summer-dry areas where they were taken more frequently in winter–spring, and less frequently in summer–early autumn. Counts were taken at 15 or 20 cm intervals down the soil profile with the initial count being 15 or 20 cm below the soil surface. At each site, the NMM was calibrated by regressing relative count rate against soil volumetric soil water content (SWC) for a range of water contents from wet to dry. Volumetric SWC was calculated from gravimetric SWC and soil bulk density using the equations outlined by White and Ridley (1998); all soil water data were expressed in millimetres.

Soil moisture characteristics, *hydraulic conductivity and bulk density.* Laboratory estimates of SWC that approximated wilting point, field capacity and saturation were determined for the different soil types at each site using

Table 6. Total annual rainfall (mm) for each year of the experiment, and long-term average (LTA) for each site

Site	Yearly rainfall (mm)					LTA (mm)
	1998	1999	2000	2001	Mean	
Barraba	724	667	602	—	664	694
Manilla	848	666	617	—	710	654
Nundle	1074	822	903	—	933	834
Carcoar	—	795	842	574	737	935
Wagga Wagga	526	535	622	443	532	574
Bendigo	577	592	732	400	575	643
Harrogate[A]	458	471	612	536	519	558
Yass	694	721	671	656	686	647
Maindample	765	750	775	—	763	719
Ruffy	625	660	715	—	667	804
Vasey	641	469	563	—	558	625
Albany	717	706	642	—	688	810

[A]Harrogate data was derived from the SILO dataset (Jeffery *et al*. 2001).

hanging water columns (0–10 kPa) and ceramic pressure plates at water potentials of –1, –10 and –1500 kPa, respectively. Measurements were made on intact cores (6–7 cm diameter by 5 cm high) at potentials of 0, –1, –5, –10, –100 and –1500 kPa.

Soil chemical analyses. Soil cores (0–10 cm depth, 2.5–5.0 cm diameter, 10–60 per plot) were taken from a minimum of 2 contrasting treatments at each site. These treatments were usually the control and the most extreme nutrient treatment. Samples were collected twice; just before or shortly after the national experiment commenced in 1997–98, and again in spring 2000. Samples from all sites (except Yass) were sent to the State Chemical Laboratory, Victoria, for analyses. Samples were ground to pass through a 2 mm sieve dried at 40°C and analysed using the methods described by Rayment and Higginson (1992) for: (i) pH — 1 : 5 water and 1 : 5 $CaCl_2$; (ii) electrical conductivity (EC) — dS/m, 1 : 5 water; total soluble salts — % w/w; plant-available phosphorus (P) — mg/kg soil, Colwell (Colwell 1963), Bray (No. 1) (Bray and Kurtz 1945), and Olsen (Olsen *et al*. 1954); (iii) plant-available sulfur (S) — mg/kg soil (Blair *et al*. 1991); and (iv) exchangeable cation concentrations for calcium (Ca), magnesium (Mg), sodium (Na), and potassium (K) (meq/100 g).

For each site (except Yass), soil samples (0–5 cm) were also collected each spring in a minimum of 2 contrasting treatments and analysed for labile carbon using the procedures outlined by Blair *et al*. (1995).

Towards the end of the national experiment, 2 contrasting treatments at each site (usually a control and the most extreme treatment) were sampled to a depth of 120 cm to examine the cumulative effect of several years of treatment. Samples for 0–10, 10–20, 20–40, ... 100–120 cm were dried at 40°C and analysed for pH, EC, available S and K, nitrate-nitrogen (N) and ammonium-N (Rayment and Higginson 1992). At north-east Victoria these samples were taken in autumn 2001 to estimate mineral N in the soil profile before any leaching over winter occurred. This was not possible at all other sites and samples were taken in spring 2001.

At all sites, all or contrasting treatments were sampled for earthworm numbers and species diversity (0–10 cm) in spring 2000 or 2001.

Site characterisation. For each site, the previous history of the paddock was recorded together with the latitude, longitude, elevation (m) and the long-term average annual rainfall (mm) of the nearest town or centre. Soils were classified using the Australian Soil Classification (Isbell 1996). Initial soil samples (0–10 cm) were taken before treatment application and analysed for soil chemical properties as described above (see section on ‘soil chemical analyses’). Depth (cm) to B horizon of the soil profile was also recorded.

Themes

The role of themes was to develop insights into the processes underlying the profitability and sustainability of grazing systems across the temperate HRZ. This was achieved by undertaking across-site analyses of results to draw out more general conclusions about ‘profitability and sustainability’ than could be achieved from individual site analyses alone. In part, this was done to extend results beyond each of the experimental sites. Themes served to unify sites into a ‘national’ experiment and they were fundamental to developing principles, guidelines and tools for producers.

All sites collected a ‘minimum dataset’ for each theme [as defined in the experimental protocols, Lodge (1998)]. At individual sites, however, more than the minimum dataset was collected for some themes, reflecting the focus of each site (Table 7).

For each theme, teams drawn from across the site teams, each with a nominated convenor, were established following the December 1996 workshop. The first task of these teams was to define theme questions, which were refined as the national experiment progressed (Table 8).

Database

The SGS relational database (Scott and Lord 2003) was developed so that the large amount of data collected in the national experiment could be entered, quality-assured, stored and retrieved in a consistent and manageable way for each site. It also gave effect to the power of collecting common data to a standard protocol across sites. The database also automatically calculated various functions needed for data analysis and interpretation. This enabled rapid and detailed

Table 7. Matrix of the national experiment sites and the focus of the sites in relation to the five themes and economic analyses

Sites or subsites	Animal production	Pastures	Water	Nutrients	Biodiversity	Economics
North West Slopes	x[A]	xx	xxx	xx	xx	x
Carcoar	xx	xxx	xx	x	xxx[B]	xx
Eastern Riverina	x	xxx	xxx	xx	x	x
North-east Victoria	x	x	xxx[B]	xx	x	x
Vasey	xx[B]	xxx	xx	xx[B]	x	xx
Albany	xx	xxx[B]	xxx	x	x	xx

[A]x, xx and xxx, respectively indicates a low, medium or high emphasis for each theme at that site. [B]Location of the convener of the theme team.

examination of inter-relationships in the data, assisted by straightforward graphical display of results using 'point and click' features of Microsoft Access and Excel software. To further enhance this facility, data could be directly exported between the database and the SGS Pasture Model. The database specialist interacted with site and theme teams and the SGS modeller to implement the range of quality checks and functionality in the database for each site. Use of the database markedly increased the quality of the data, and sped up the process of data analysis.

SGS Pasture Model

The SGS Pasture Model (Johnson *et al*. 2003) was a biophysical simulation model of the grazing (soil–plant–animal) system, specifically designed to meet the needs of the national experiment. It was characterised by its user-friendliness and a highly intuitive interface. It was continually being developed by the modeller, interactively with each of the national experiment site teams, with an emphasis on its use as a research tool for data exploration and interpretation. It provided a cohesive structure for analysing the behaviour of the pasture biophysical system, and data from the national experiment were used to set parameters for the model. It was used by all theme teams (except biodiversity, which it was not designed for) to explore ideas that emerged from their data analysis via modelled scenarios, and to examine the theme questions more thoroughly, for example by exploring differences in contrasting treatments at selected sites using long-term (1971–2001) simulations based on daily weather data (see below).

Included in the model were complex, dynamic interactions between different components, which improved our understanding of grazing systems. Principal features of the model were its water and nutrient dynamics with regard to soil water infiltration and through drainage, runoff (surface and subsurface), transpiration, evaporation (canopy, litter and soil) and nutrient flow (N, P, K and S). Herbage accumulation of different species types was determined in response to light, temperature and soil nutrient status, and multiple pasture types could be incorporated

Table 8. Theme questions/objectives in the national experiment

Water

1. What is the impact of soil and vegetation type (pasture with and without trees) on the quantity of water used by a grazing system and the pathways of water movement in the landscape?
2. What effects do different management practices (grazing management options and fertiliser use) have on the quantity of water used by a grazing system and the pathways of water movement in the landscape?
3. What are the best combinations of vegetation type (pasture with and without trees) and management practices to maximise production and water use by a grazing system?
4. What information, skills and knowledge do producers need to adopt practices that make better use of water, and what policy guidelines should be developed to encourage a significant number of producers to adopt these practices?

Nutrients

Quantify the positive and negative effects of N and applied P both on and off-site on:

1. Pasture and animal productivity;
2. Soil acidification; and
3. P and N concentrations in runoff waters.

Pastures

For the national experiment pasture types within the edaphic and climatic regions to which they are suited, determine:

1. What is the effect of farm management (e.g. fertiliser use, grazing management options) on pasture production and stability?
2. What is the impact of climatic and edaphic factors on pasture productivity and stability?
3. Which combinations of pasture and management in different edaphic and climatic zones provide productive and stable grazing systems?

Pasture stability was defined as the persistence of a given botanical composition through time.

Animal production

1. What effect do the different grazing strategies have on pasture utilisation at the various sites?
2. What are the grazing management strategies that promote economical and sustainable grazing at each site?
3. What is the efficiency of meat production relative to plant production, rainfall and evapotranspiration under the different grazing systems at each site?
4. Develop, in conjunction with other themes, a response curve across sites for animal productivity from rainfall, using a multi-variate model, including rainfall, evapotranspiration, soil water, growing season, etc.

Biodiversity

1. What is the impact on biodiversity of using land for grazing?
2. What are the relationships between biodiversity, productivity and sustainability of grazing systems?
3. Develop tools to monitor and manage biodiversity.

Economics

What are the relative profitabilities of the national experiment treatments?

Table 9. Pasture type and stocking rates (DSE/ha) for the six SGS National Experiment site simulations used to examine the effects of stocking rate and grazing management on pasture herbage accumulation, stocking rate, supplements fed and number of grazing Merino wethers

	Albany	Vasey	Maindample	Wagga Wagga	Carcoar	Barraba
			Stocking rate (DSE/ha)			
Low	7	7	9	2	8	2
Medium	14	10	12	4	12	4
High	21	13	15	6	16	6
			Pasture type			
	Kikuyu and sub. clover	Phalaris and sub. clover	Phalaris and sub. clover	C_3 and C_4 native perennial	C_3 and C_4 native perennial	C_4 and C_3 native perennial

(annuals–perennials, and legumes–grasses). Animal growth was modelled using metabolisable energy with allowances for pregnancy and lactation. The model accommodated grazing management options ranging from set-stocked to rotational, or actively managed (i.e. grazing or resting as required to optimise management goals).

Use of the SGS Pasture Model for theme explorations

Theme requirements for output from the model were met in 2 ways. First, all sites ran simulations using site parameter values (Tables 9, 10 and 11) and local SILO (Jeffery *et al*. 2001) daily climate data sets (1971–2001). These simulations compared set-stocked and rotationally grazed treatments grazed at low, medium and high rates (Table 9) using Merino wethers. Stocking rates were selected to be appropriate for the pasture types (Table 9) at each site. Also, at each site a variable stocking rate was implemented to maintain pasture herbage mass at 1500 kg DM/ha, with decisions on stocking rate adjustments being made (by the model) every 7 days.

Table 10. Soil parameter values for depth (bottom of the horizon, cm), saturated water content (θ_s, %), drainage point (θ_d, %), saturated hydraulic conductivity (K_s, cm/day) and texture for the surface A, B1 and B2 horizons for the six SGS National Experiment site simulations

	Albany	Vasey[A]	Maindample[A]	Wagga Wagga	Carcoar	Barraba[A]	Esperance[A]
				Surface			
Depth	2	5	5	10	10	10	2
θ_s	56	45	40	43	43	43	35
θ_d	41	30	33	29	25	29	8
K_s	30	2	28.5	5	10	5	60
Texture	Sand	Sandy loam	Loamy sand	Sandy loam	Sandy loam	Clay loam	Sand
				A horizon			
Depth	40	30	40	50	60	50	100
θ_s	40	40	40	43	43	43	35
θ_d	19	30	32	28	25	28	8
K_s	42	3	1.1	15	10	15	60
Texture	Sand	Sandy clay loam	Silty clay loam	Sandy clay loam	Light clay	Medium clay	Sand
				B1 horizon			
Depth	110	110	120	100	100	100	200
θ_s	42	50	38	38	40	38	30
θ_d	37	35	32	23	20	23	25
K_s	10	2	0.5	19	1	19	1
Texture	—[B]	Medium–heavy clay	Medium clay	Medium clay	Medium clay	Medium clay	Clay
				B2 horizon			
Depth	300	300	300	300	300	300	300
θ_s	42	50	38	38	40	38	30
θ_d	33	40	32	20	20	20	25
K_s	55	2	0.5	4	1	4	1
Texture	Sandy clay	Heavy clay	Medium clay	Heavy clay	Medium clay	Heavy clay	Clay

[A]Parameter values for the 4 standard soil types. [B]Laterite rock.

Second, for each of 6 national experiment sites or subsites (Barraba, Carcoar, Wagga Wagga, Maindample, Vasey and Albany) simulations were constructed based on 4 contrasting pasture types (Table 9) and 4 contrasting soil types (2 duplex soils — based on Vasey and Maindample sites, a well drained, heavy textured soil — based on the Barraba site, and a deep sand — based on the Esperance site) (Table 10) and run for 31 years of daily SILO climate data (1971–2001). Pasture types used to provide contrasting growth patterns were a deep-rooted C_4 sown perennial (kikuyu, *Pennisetum clandestinum* Hochst. Ex Chiov., 250 cm rooting depth), a medium-rooted C_3 sown perennial (phalaris, 120 cm rooting depth), a C_4 native perennial [redgrass (*Bothriochloa macra* (Steud.) S. T. Blake, 120 cm rooting depth], and, a C_3 annual [ryegrass (*Lolium rigidum* Gaudin), 80 cm rooting depth]. Each pasture type also had subterranean clover (*Trifolium subterraneum* L.) as a companion legume (rooting depth 80 cm). All pasture types were grazed by Merino wethers and set-stocked at rates of 8 (C_3 annual and C_4 native perennial) or 12 DSE per hectare (C_3 and C_4 sown perennial). For these simulations, profile depth was standardised at 300 cm, so that drainage referred to the movement of water beyond this depth.

Economic analyses

SGS explored both macro (industry) and micro (individual producer) economic analyses. Initially, the focus was at the macro level using a dynamic programming approach (Kennedy 1986) to identify management ‘pathways’ that optimised the profitability and sustainability of grazing systems. Explicitly considered in a dynamic way were the temporal and biological dimensions of resource management problems and, in particular, the future impact of current decisions. The SGS Pasture Model generated key biological relationships that underpinned the resource managers’ choices. However, the management team judged that this approach was unlikely to deliver useful results within the timeframe of the SGS Program, and so it was discontinued in 1999.

Prompted by the national experiment review (Johnson *et al*. 2001), a procedural tool was developed that addressed producer requirements for a balanced appraisal of alternative management practices and systems (Barlow *et al*. 2003). This tool combined both an equivalent annual net return analysis, and a standard 11-point rating system for key natural resource sustainability elements, for both on- and off-farm impacts.

Interactions with producers

Producer input into the national experiment. The formation of a producer planning group ensured that producers were actively involved in planning the national experiment for more than 12 months before SGS began (Mason *et al*. 2003*a*). Steering group producers led discussion groups at the research planning workshop in December 1996 and participated in technology transfer advisory groups that reviewed the final site research plans, leading to substantial changes in some cases. Local producers actively participated in site research planning meetings at the start of SGS and provided on-going practical advice about the management of each site. Most sites also had strong linkages to the SGS Regional Producer Network via the local regional committee.

Rapid delivery of research findings to producers. As part of a strongly producer-driven program (Mason *et al*. 2003*a*), SGS initiated processes to hasten the delivery of information from the national experiment to producers. These included locating national experiment sites on commercial properties to encourage rapid uptake of successful grazing management systems. At the western Victoria site, for example, the collaborating producer initiated rotations and pasture budgeting for his whole property after seeing the benefits of having more control through rotational grazing management. Researchers in the national experiment shared preliminary research findings (‘hunches’) with producers at the first SGS National Forum (Armidale, March 2000) and a summary was provided to all those actively involved in SGS, including PROGRAZE presenters. As a result, producers were able to provide feedback directly to researchers at the forum and to participate more effectively in the harvest year (Mason *et al*. 2003*a*). Researchers in the national experiment actively contributed articles to ‘Prograzier’ (an SGS publication for graziers, Mason *et al*. 2003*a*), culminating in 2001–2002 special issues of ‘Prograzier’ (1 issue per theme)

Table 11. Maximum leaf photosynthetic rate (P_{max}, mg $CO_2/m^2.s$) at the optimum temperature and the minimum, optimum and maximum temperatures for growth of the four standard pasture grasses and subterranean clover

	Phalaris	Kikuyu	Redgrass	Annual ryegrass	Subterranean clover
			Temperature (°C)		
Minimum	5	8	15	0	5
Optimum	22	33	30	20	25
Maximum	35	37	32	30	35
			P_{max} (mg $CO_2/m^2.s$)		
	0.7	1.01	0.6	0.7	0.8

that communicated the SGS research findings in an integrated way. In 2001, the content of PROGRAZE courses was refined on the basis of the national experiment's results, to include information about understanding and managing the water cycle in grazing systems. Broader sustainability issues were also introduced in a new product for producers called PROGRAZE Update.

Monitoring and evaluation

Included in the national experiment were processes for on-going monitoring and evaluation. In March each year, researchers met to review progress and direction based on site reports and to provide input into themes, which reported each June. After a further 6 months the research executive again reviewed the national experiment progress and direction. Additionally, there were initiatives that arose from the annual meetings of the SGS management. This created an environment of active and continuous improvement.

The national experiment was externally evaluated twice, first at the mid-term review of SGS, conducted independently by VCG Australia Pty Ltd (1998), and then by the review of Johnson *et al*. (2001) that largely confirmed the outcomes of the mid-term review. They concluded that:

> 'The SGS national experiment is well placed to make a significant contribution to the program, the grazing industry and its communities. It is built from excellent research sites extending across the nation. It is linked through innovative processes. It has clear links with client producers. It is about to embark on a novel product development approach (the harvest year) of huge potential benefit to its customers that will stretch its resources to the limits. The review team believes that the program possesses the necessary commitment, planning and management skills required to reach a successful outcome.'

The review further observed that '… the theme concept is an innovative response to the challenges that the SGS goal imposes, and has the potential to change the way we do systems experiments in future', but cautioned that '… there is much to be done if this approach is to realise its potential'. This led to a refocusing of the national experiment for the remainder of SGS and the harvest year, with the appointment of post-doctoral support for the water, nutrients, pastures and animal production themes.

The social dynamics of the national experiment researchers, especially those at the New South Wales north-west slopes site, was also studied, and leadership and influence patterns elucidated (Andrew *et al*. 2003; Price 2003).

Conclusions

A key feature of the national experiment design was that it provided a mechanism through which diverse sites, encompassing a wide range of environmental conditions and experimental designs, could collect a common data set in a uniform way so that issues beyond the site level could be explored. Essential to this process was the provision and use of both the database and modelling tools that enabled across-site issues to be examined by a unique mixture of data analysis and modelling scenarios, which had not been previously attempted at this scale in the Australian grazing industries. The unifying theme process enabled value to be added to the work of the sites by collecting and analysing a broad range of production and sustainability data.

How well this process worked was reported by Andrew *et al*. (2003), along with how well it enabled the SGS to achieve its objectives. As judged by peer and independent review, the processes implemented in the national experiment were a success. We believe that this new research paradigm will change the face of large-scale grazing systems R&D.

Some of these processes were severely tested in the harvest year (Mason *et al*. 2003*a*), the review of which [see Mason *et al*. (2003*b*) for a summary] is a valuable adjunct to this account of the national experiment — the national experiment participants had a strong input into this review. How well the findings of the national experiment were captured and translated into producer adoption of more productive and sustainable grazing practices is discussed further by Allan *et al*. (2003), Andrew (2003), Andrew *et al*. (2003), Mason *et al*. (2003*b*), Simpson *et al*. (2003) and Nicholson *et al*. (2003).

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