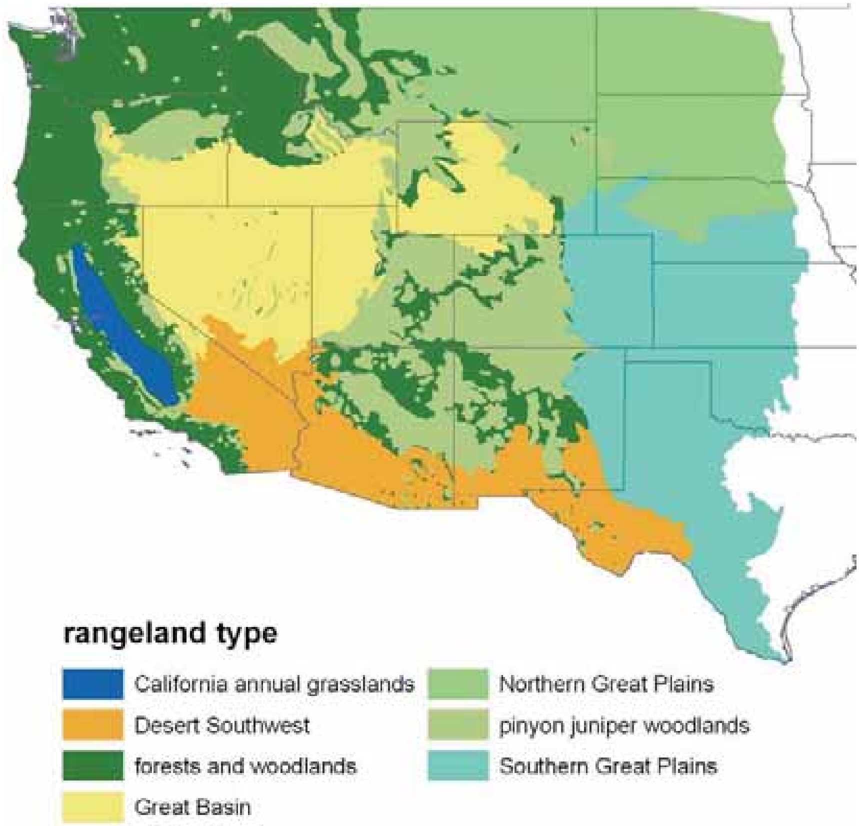
Figures



Rangeland types are aggregations of ecoregions within a type as delineated by the National Geographic Society as detailed at: www.nationalgeographic.com/wildworld/terrestrial.html
The forests and woodlands type encompasses a multitude of interspersed areas of diverse forest and woodland species.

FIGURE 1: **Rangeland types in the contiguous Western United States** *(Chapter IV)*

APPROACH 1 Reward changes in management	
PRO	CON
Landowners know compensation values prior to participation Easier, faster, cheaper	Risk of error
	SOLUTIONS Estimate errors through measurement and modelling Smooth out variation by increasing spatial extent Discount credits as needed

APPROACH 2 Reward changes in C stocks	
PRO	CON
Greater accuracy	
Potentially higher revenue and uptake	More complex methodology
Can achieve the balance required by markets, producers and science	Higher transaction costs
	SOLUTION Increased quality of credits may offset increased data gathering costs

FIGURE 2: **Comparison of two core approaches for protocol design** *(Chapter IV)*

Options for rewarding changes in C stocks

Option 1. Site-specific measurement	
PRO	CON
Potentially most accurate option	Expensive Low scalability
	SOLUTION Combine with other methods in a combination methodology

Option 2. Performance standard	
PRO	CON
Implementation simpler than Option 1 An accepted approach for high-quality credits	Value of performance standard determined by its final design
	SOLUTION Careful protocol design and development

Option 3. Hybrid – performance standard with some site-specific assessment	
PRO	CON
A balance between Options 1 and 2	Incompatibility of some blended elements?
	SOLUTION Select feasible desired hybrid elements

FIGURE 3: **Comparison of options for rewarding changes in C stocks** *(Chapter IV)*

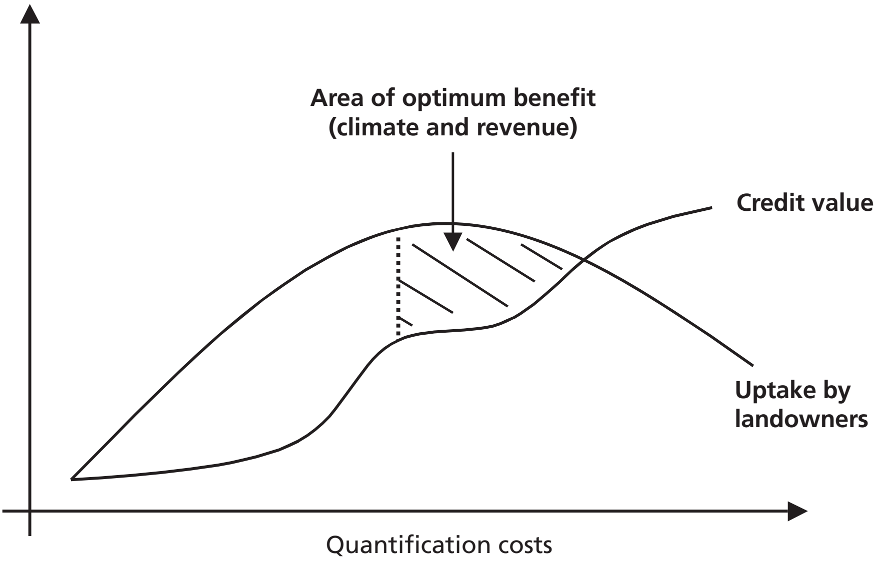


FIGURE 4: **Locating the area of optimum benefit** *(Chapter IV)*

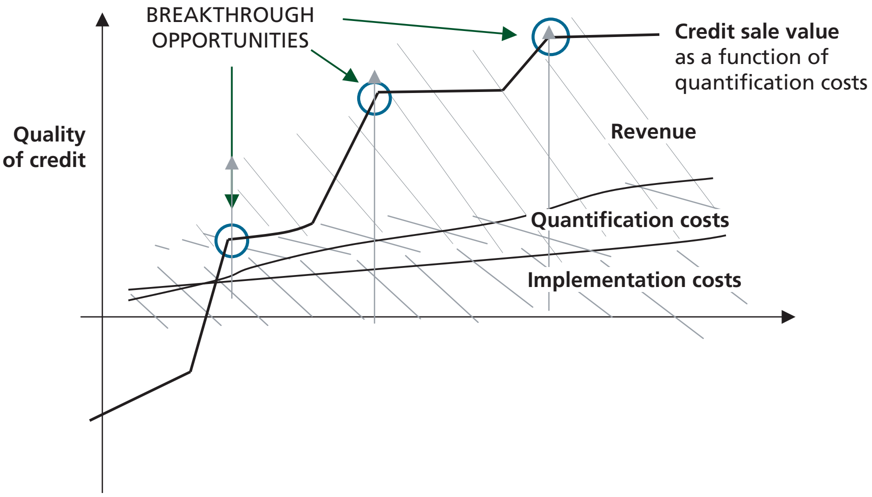


FIGURE 5: **Breakthrough opportunities for protocol design. A theoretical representation of the economic decision-making landscape for quantification methodologies or performance standards** *(Chapter IV)*

Direct method		Pro	Con	Can be used
Soil core samples + dry combustion	Combustion and analysis occur in the laboratory	Established and reliable method	Cost-prohibitive on per-project basis	In combination with other methods To provide model input data To provide data for a performance standard
LIBS (Laser-induced Breakdown Spectroscopy)	On site analysis Uses laser	Analysis occurs onsite Can provide chemical analysis	Cost-prohibitive on per-project basis	
MIRS (Mid-InfraRed Spectroscopy)	Analyses core samples on-site	Analysis occurs on-site Can differentiate SOC and SIC More accurate than NIRS	Cost-prohibitive on per-project basis	
NIRS (Near InfraRed Spectroscopy)	On-site analysis	Considered a good, rapid, low-cost method	Less accurate than MIRS	
EC (Eddy covariance)	Measures ecosystem C flux from stationary towers above landscape	Increasingly robust method	Issues of error sensitivity and cost-effectiveness remain	

FIGURE 6: **Direct methods of quantifying changes in soil C stocks** *(Chapter IV)*

Source: Post *et al.*, 2001; McCarty *et al.*, 2002; Izaurralde, 2005; Izaurralde *et al.*, 1998.

Model		Pro	Con
CENTURY	Widely used for over 30 years	Provides very detailed information	Cannot model N_2O and CH_4 fluxes
DNDC	DeNitrification DeComposition GHG model	Can model N_2O CH_4 fluxes	
COMET-VR	Modified version of Century Runs on a monthly timestep	Can model N_2O CH_4 fluxes Has a Web-based interface	
DAYCENT	Modified version of Century Runs on a daily timestep	Daily timestep not required for C sequestration projects	Cannot model N_2O and CH_4 fluxes

FIGURE 7: **Comparison of ecosystem models** *(Chapter IV)*

Source: Li *et al*., 2003; Conant *et al*., 2005; Paustian *et al*., 2009; Parton *et al*., 2005; Adler, Del Grosso & Parton, 2007.

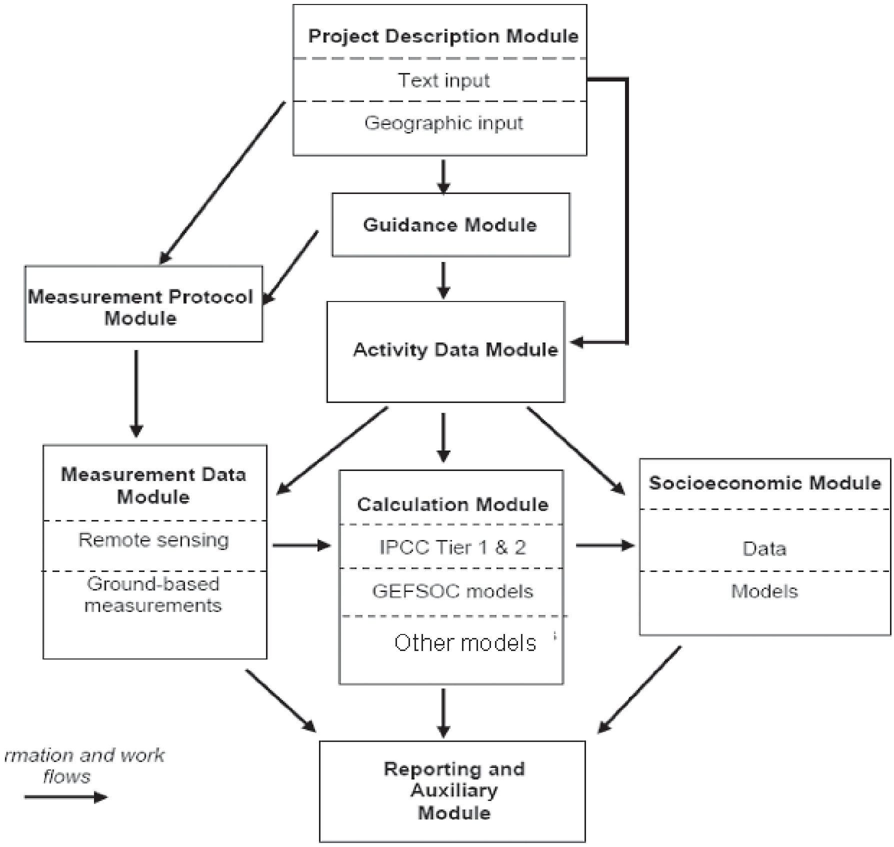
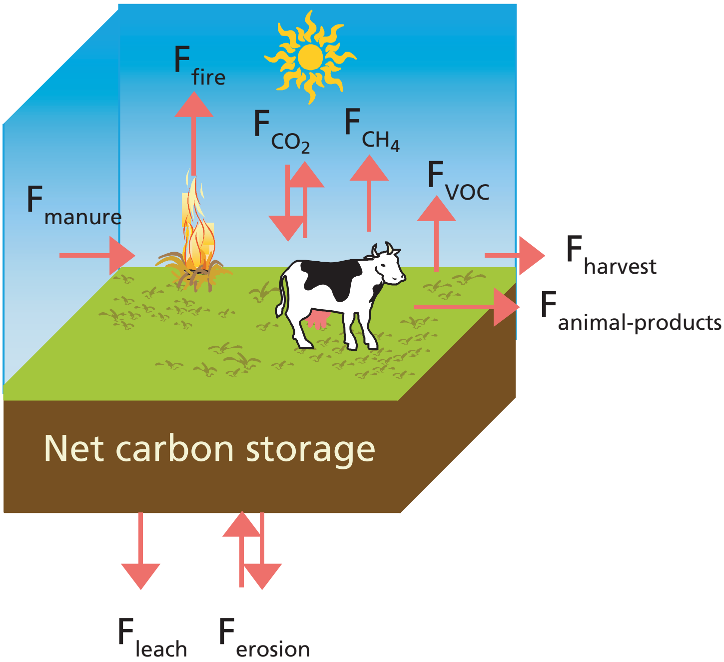
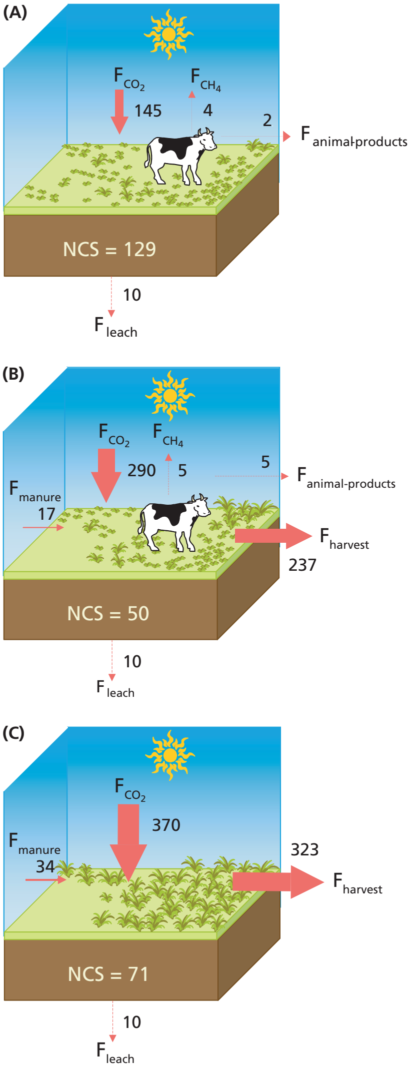


FIGURE 8: **Conceptual system overview of the CBP tool** *(Chapter V)*



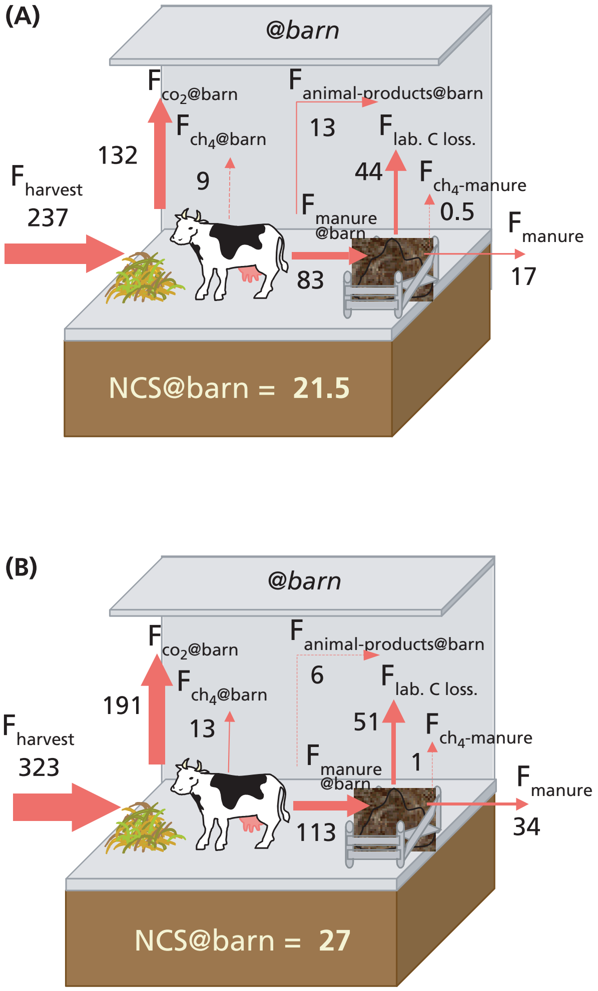
Carbon fluxes (g C/m²/year) in a managed grassland. F_{CO2} is the net CO_2 ecosystem exchange. F_{fire} is the total C loss by fire, F_{CH4}, F_{VOC} are non-CO_2 trace gas C losses from the ecosystem, as methane and volatile organic carbon, respectively. F_{manure}, $F_{harvest}$ and $F_{animal\text{-}products}$ are lateral organic C fluxes which are either imported (manure application) or exported (harvests and animal products) from the system. F_{leach} and $F_{erosion}$ are organic (and/or inorganic) C losses through leaching and erosion, respectively. Net carbon storage (NCS, see Eq. 1) is calculated as the balance of carbon fluxes.

FIGURE 9 *(Chapter VI)*



Carbon fluxes (g $C/m^2/year$) in managed European grassland systems studied by Soussana *et al*. (2007). Net carbon storage in the grassland (NCS, see Eq. 2) in grazed only (A), cut and grazed (B) and cut only (C) grasslands is calculated as the balance of carbon fluxes. For abbreviations, see Figure 9. Data are means of 2, 4 and 3 European sites for grazed only (A, meat production systems), cut and grazed (B, meat and dairy production systems) and cut only (C, dairy production systems) grasslands. A standard F_{leach} value (10 g $C/m^2/year$) was assumed for all sites. C exports in animal products were assumed to reach 2 and 20 % of C intake for meat and milk production, respectively (see text). Grazed sites: Hungary, France, Italy (see Allard *et al*., 2007; Soussana *et al*., 2007; Table 9). Cut and grazed sites: Scotland, Ireland and the Netherlands (see Soussana *et al*., 2007; Table 9). Cut sites: Switzerland (see Ammann *et al*., 2007; Table 9). A positive value of NCS and Att-NCS denotes a sink activity of the grassland ecosystem.

FIGURE 10 *(Chapter VI)*



Carbon fluxes (g C/m²/year) in managed European grassland systems studied by Soussana *et al*. (2007). Net carbon storage in the barn (NCS@barn) in cut and grazed (A) and cut only (B) grasslands are calculated as the balance of carbon fluxes. $F_{CO2@barn}$, $F_{animal\text{-}products@barn}$, $F_{labile\text{-}C\text{-}losses}$ are, respectively, CO_2 emissions, C exports in animal products from ruminants, CO_2 losses from microbial degradation of farm effluents during storage and after spreading. $F_{CH4@barn}$ and $F_{CH4\text{-}manure}$ are the CH_4 emissions at barn from enteric fermentation and farm effluents, respectively. For other abbreviations, see Figure 9. Carbon fluxes at barn were estimated assuming the same type of production (meat or milk) in the barn and in the grassland and solid manure (see Eq. 4). C exports in animal products at barn were assumed to be 2 and 20 % of C intake for meat and milk production, respectively (see chapter VI Mitigating the greenhouse gas balance of ruminant production systems through carbon sequestration in grasslands).

FIGURE 11 *(Chapter VI)*

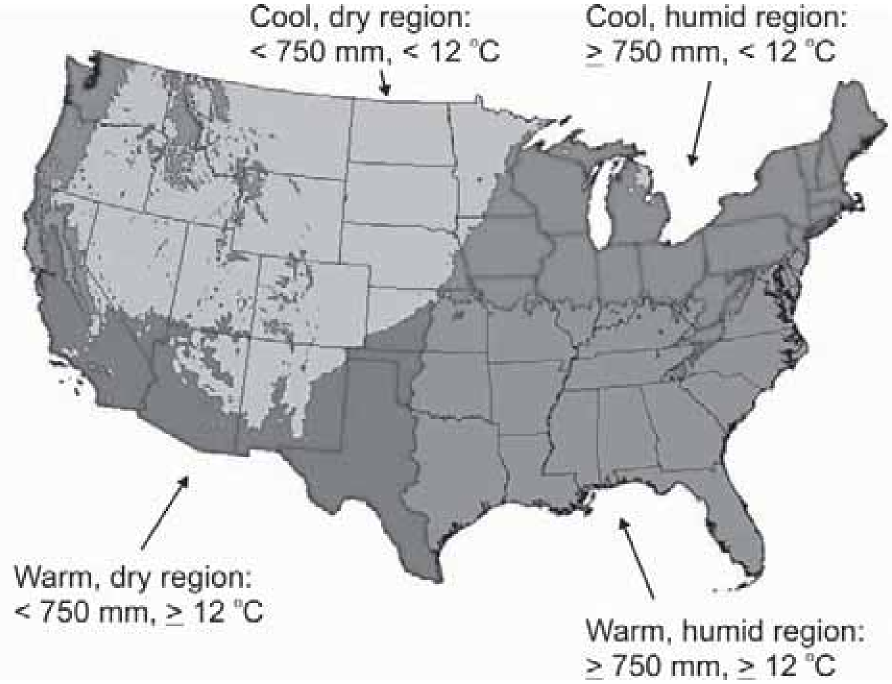


FIGURE 12: **Delineation of major climatic zones in the United States based on mean annual temperature and precipitation** *(Chapter VIII)*

Source: produced by H.J. Causarano using the Spatial Climate Analysis Service (www.ocs.ors.orst.edu/prism/).

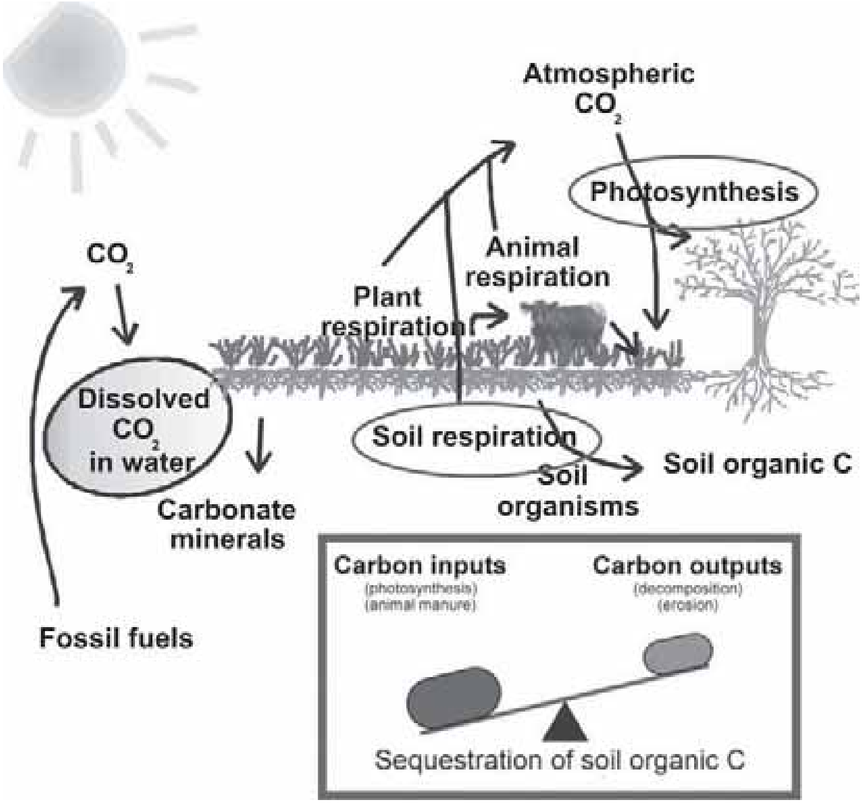


FIGURE 13: **Simplified C cycle showing the major fluxes of C via photosynthesis and respiration with the net balance affecting SOC. When C inputs to soil exceed C outputs, then soil can be considered a sink for CO_2 (soil C sequestration). When C inputs are lower than C outputs, then soil becomes a net source of CO_2 to the atmosphere** *(Chapter VIII)*

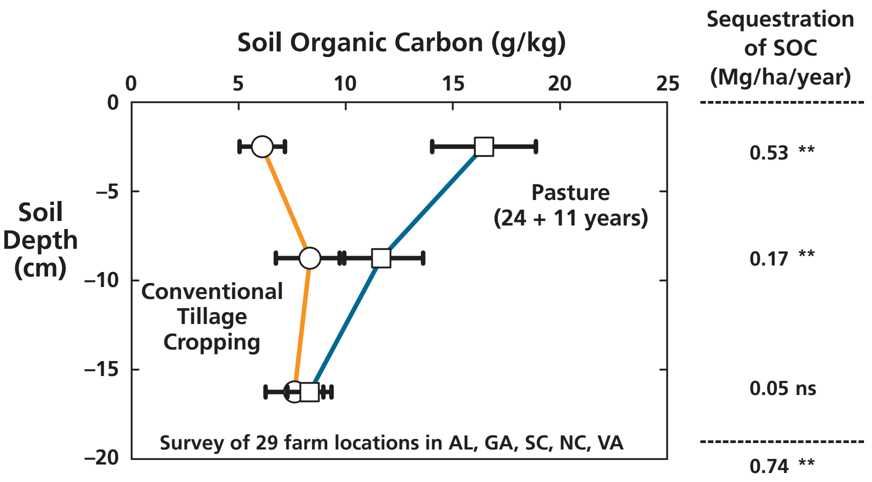
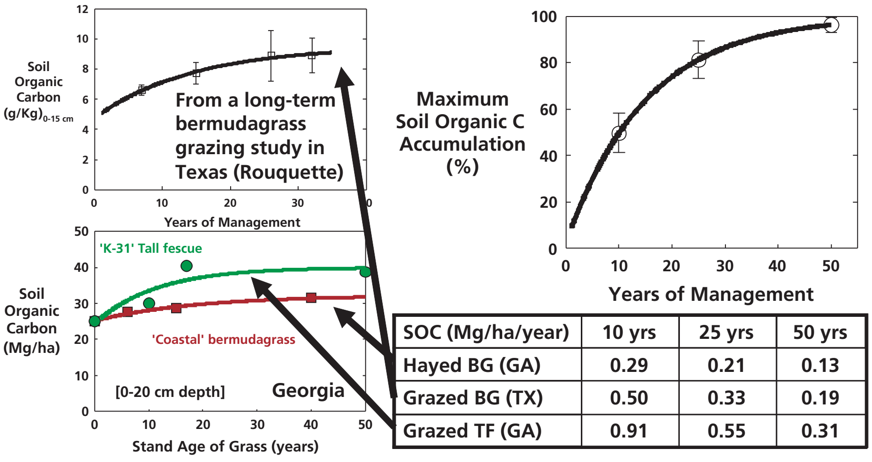


FIGURE 14: **SOC concentration (and calculation of sequestration rate) as a function of depth and land use across 29 farm locations in the southeastern United States** *(Chapter VIII)*

Source: data from Causarano *et al*. (2008).



SOC (Mg/ha/year)	10 yrs	25 yrs	50 yrs
Hayed BG (GA)	0.29	0.21	0.13
Grazed BG (TX)	0.50	0.33	0.19
Grazed TF (GA)	0.91	0.55	0.31

FIGURE 15: **SOC as a function of years of management under grazed bermudagrass in Texas (upper left panel) and hayed bermudagrass and grazed tall fescue in Georgia (lower left panel). Upper right panel is the distillation of data into a maximum accumulation curve. Lower right box reports SOC sequestration for each site at 10, 25 and 50 years** *(Chapter VIII)*

Source: data from Wright, Hans and Rouquette (2004) in Texas and from Franzluebbers *et al*. (2000) in Georgia.

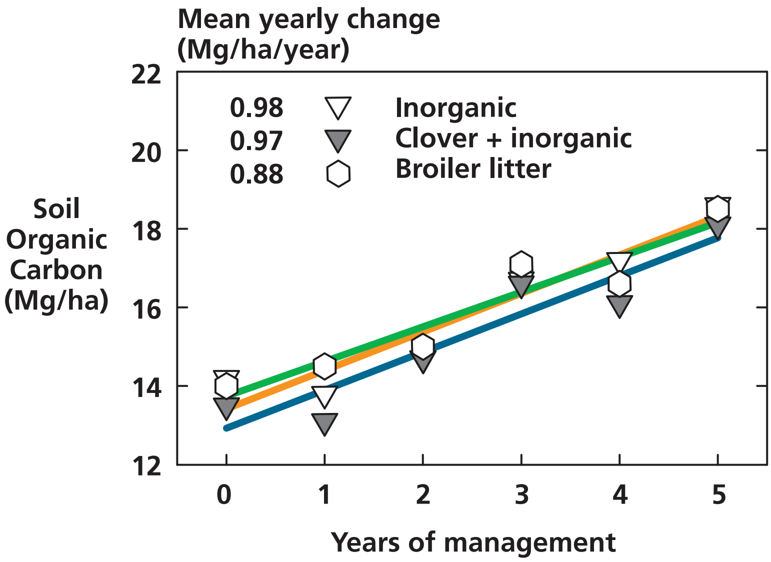


FIGURE 16: **SOC as a function of years of management and source of nutrients on a Typic Kanhapludult in Georgia** *(Chapter VIII)*

Source: data from Franzluebbers, Stuedemann and Wilkinson (2001).

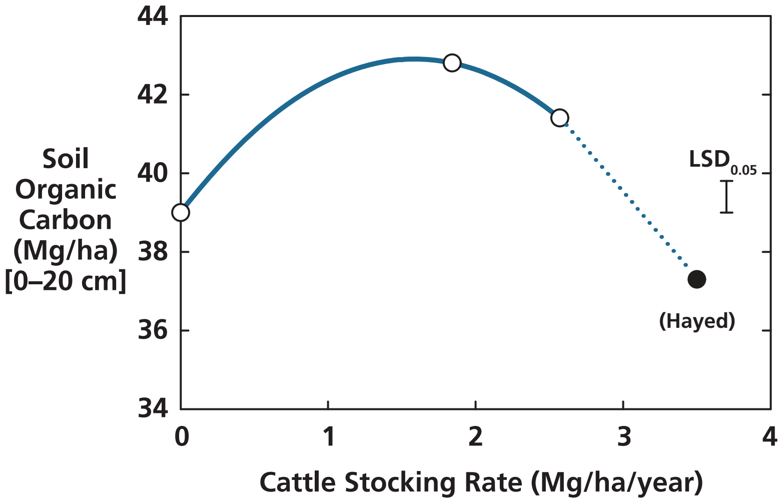


FIGURE 17: **SOC at the end of five years of different cattle stocking rates on a Typic Kanhapludult in Georgia. Filled symbol at right represents hayed forage removal (i.e. high utilization pressure, but not grazed)** *(Chapter VIII)*

Source: data from Franzluebbers, Stuedemann and Wilkinson (2001).

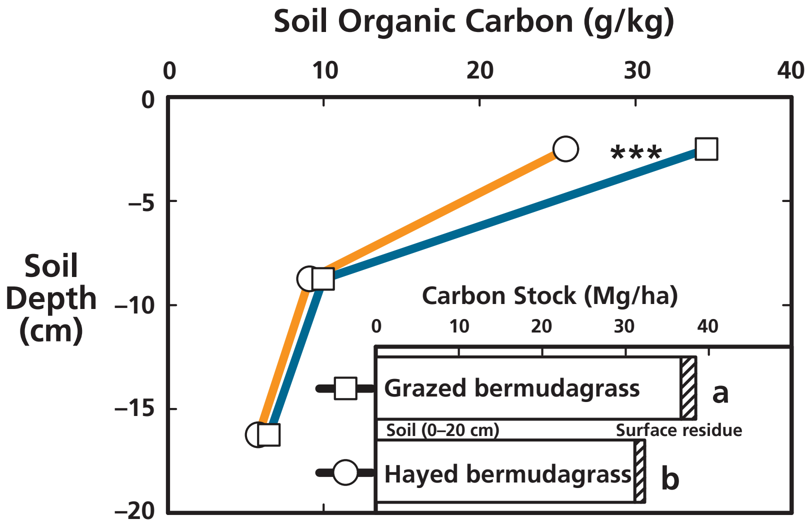


FIGURE 18: **SOC depth distribution and C stock as affected by grazed and hayed management on Typic Kanhapludults in Georgia** *(Chapter VIII)*

Source: data from Franzluebbers *et al*. (2000).

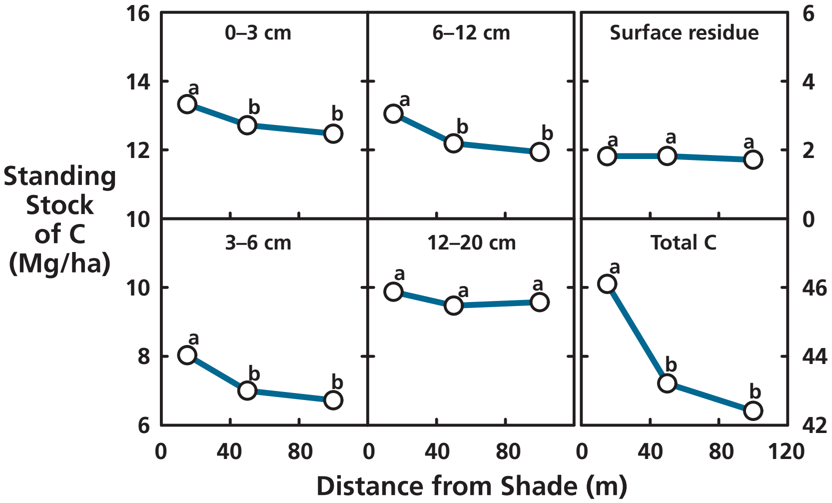


FIGURE 19: **SOC distribution vertically (by depth) and horizontally (by distance from shade) within coastal bermudagrass pastures on Typic Kanhapludults in Georgia** *(Chapter VIII)*

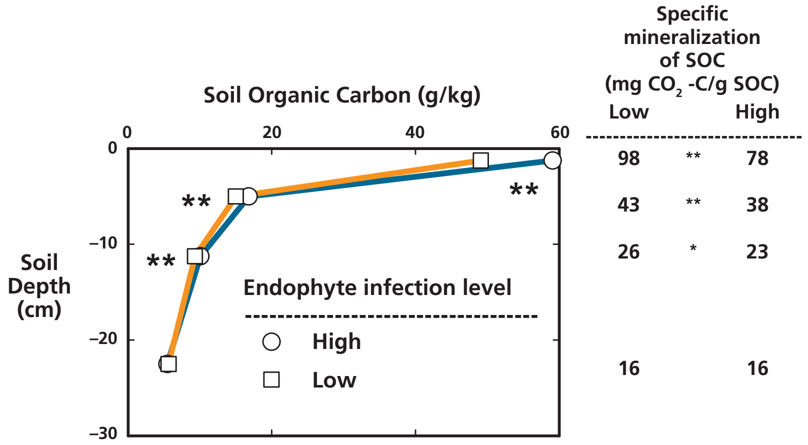


FIGURE 20: **SOC depth distribution as affected by endophyte infection frequency of tall fescue on a Typic Kanhapludult in Georgia** *(Chapter VIII)*

Source: data from Franzluebbers *et al*. (1999).

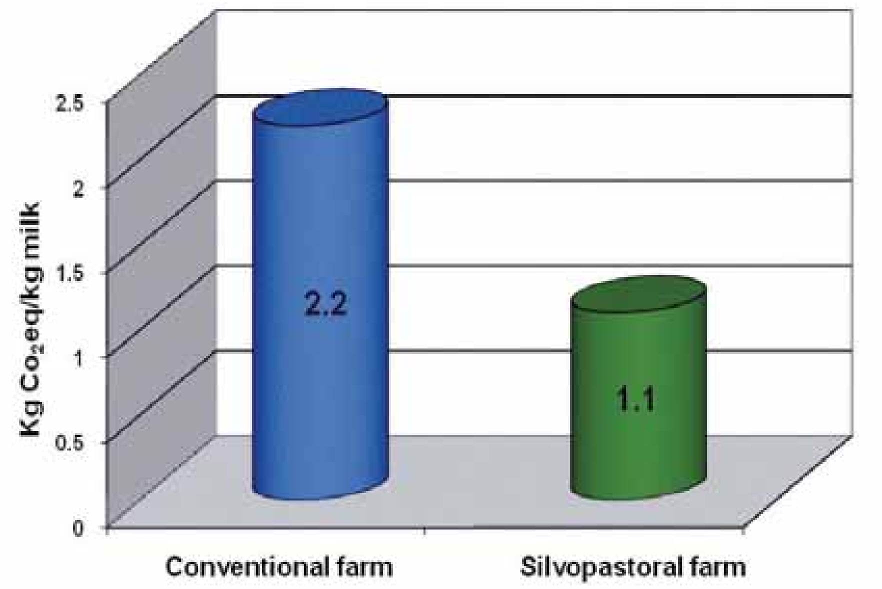


FIGURE 21: **Estimated emissions (CO2 eq) per kg of milk produced in conventional and silvopastoral farms in Esparza, Costa Rica** *(Chapter X)*

Source: data from GEF silvopastoral project, 2007.

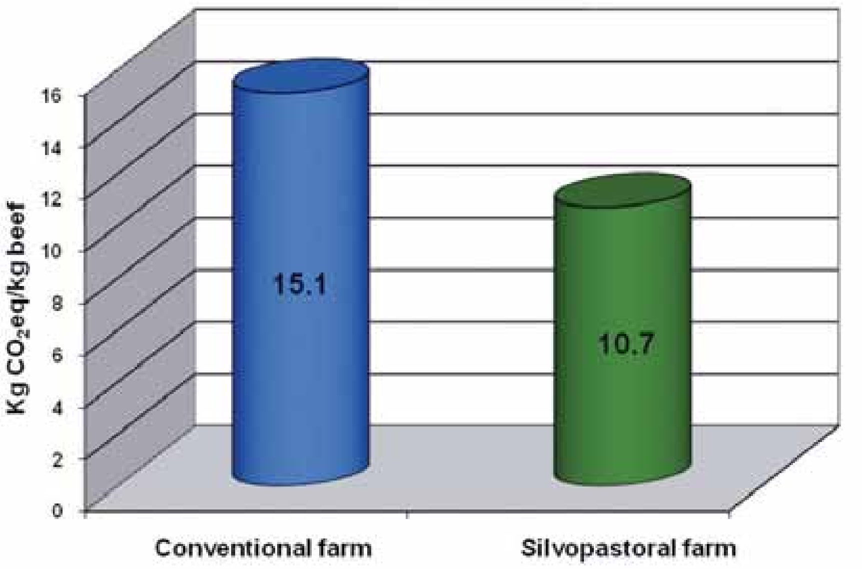


FIGURE 22: **Estimated emissions (CO2 eq) per kg of beef produced in conventional and silvopastoral farms in Esparza, Costa Rica** *(Chapter X)*

Source: data from GEF silvopastoral project, 2007.

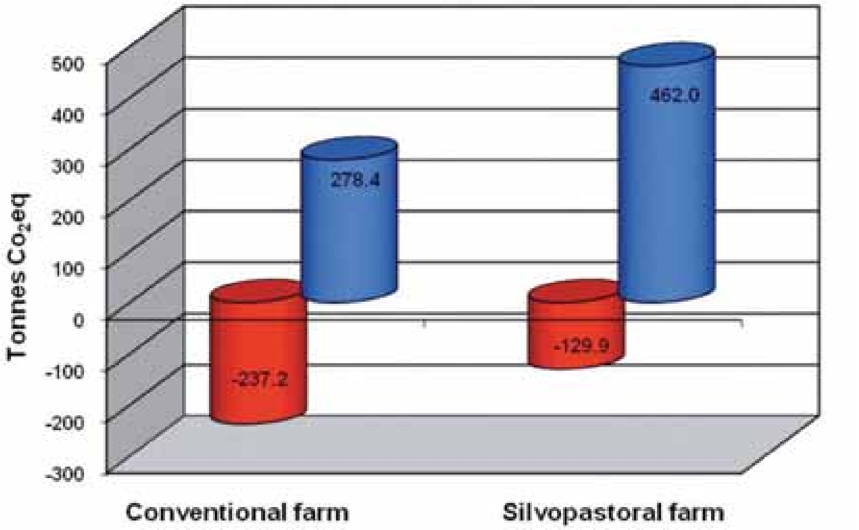
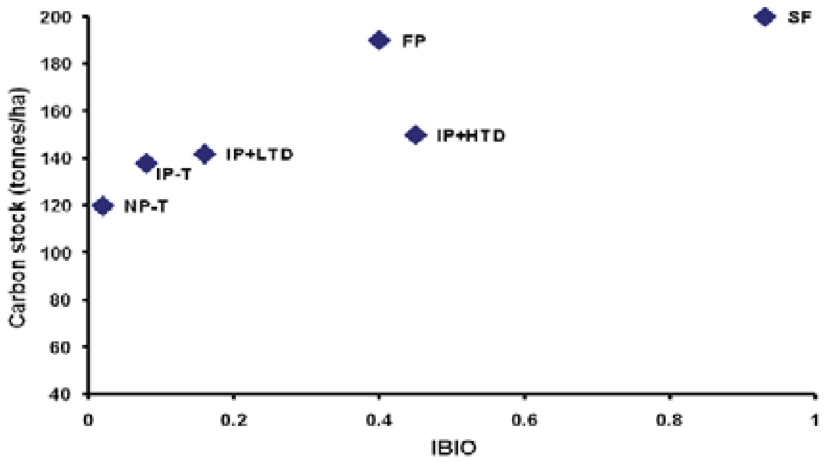


FIGURE 23: **Emissions (red) and sequestered carbon (blue) in conventional and silvopastoral farms** *(Chapter X)*



IP-T = improved pasture without trees; NP-T = natural pasture without trees; IP+LTD = improved pasture with low tree density; IP+HTD = improved pasture with high tree density; FP = forest plantation; SF = secondary forest

FIGURE 24: **Relationship between carbon stocks and index for biodiversity (IBIO) with different pasture, silvopastoral and other land uses, Esparza, Costa Rica** *(Chapter X)*

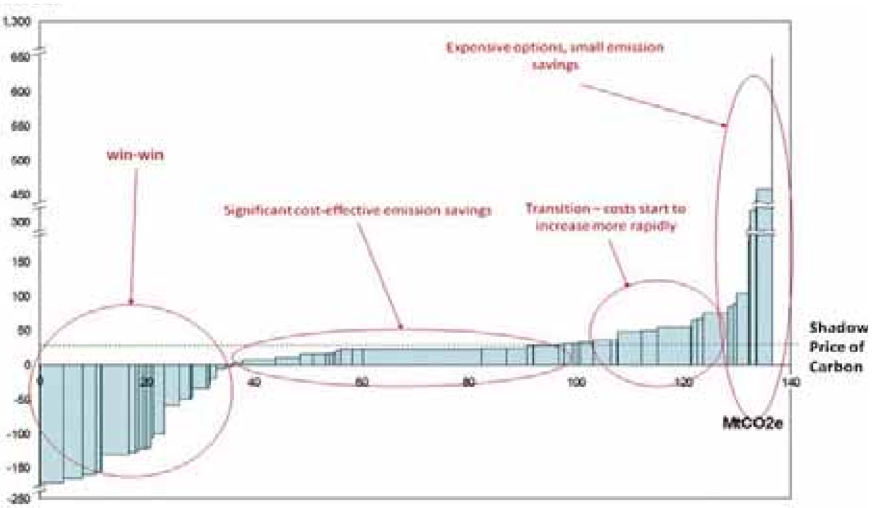
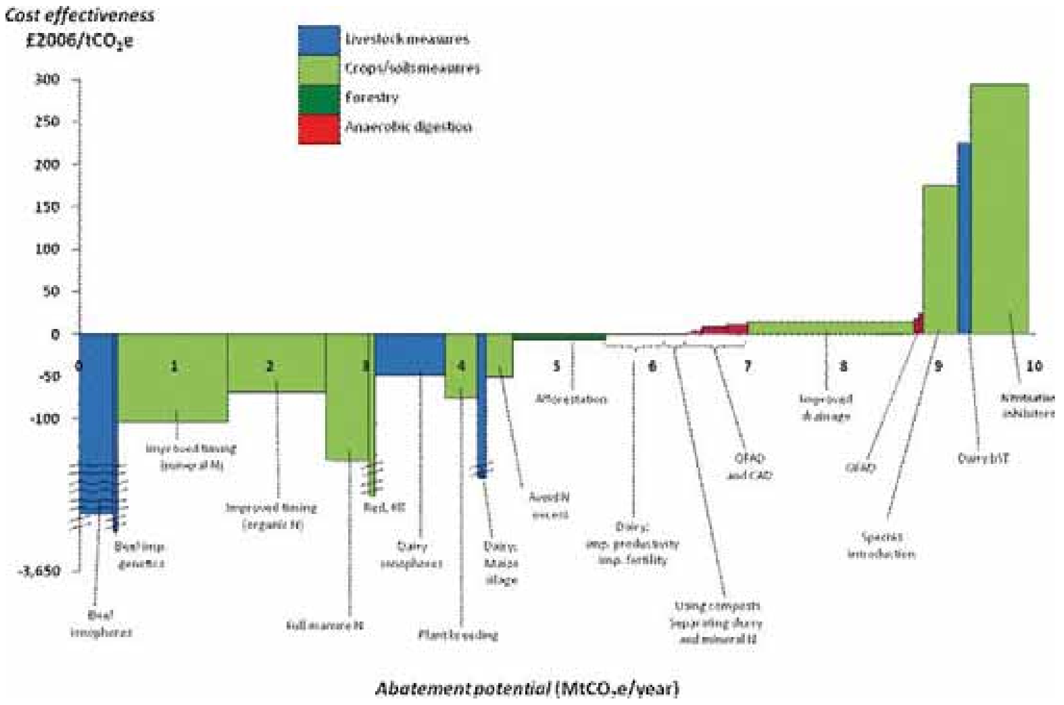
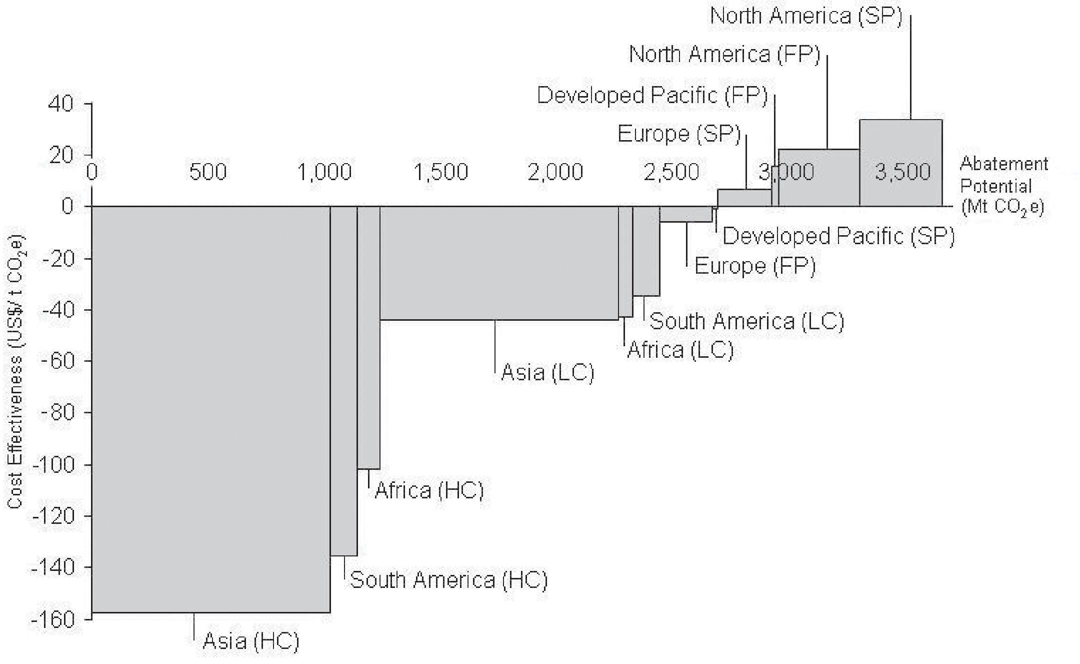


FIGURE 25: **Developing an efficient mitigation budget from a MACC** *(Chapter XI)*



OFAD = on-farm anaerobic digestion; CAD = central anaerobic digestion.

FIGURE 26: **United Kingdom MACC feasible (mitigation) potential, 2022** *(Chapter XI)*



LC = low carbon price; HC = high carbon price; SP = slow pyrolysis; FP = fast pyrolysis.

FIGURE 27: **Marginal abatement cost curve of biochar projects in developed and developing regions for 2030** *(Chapter XI)*

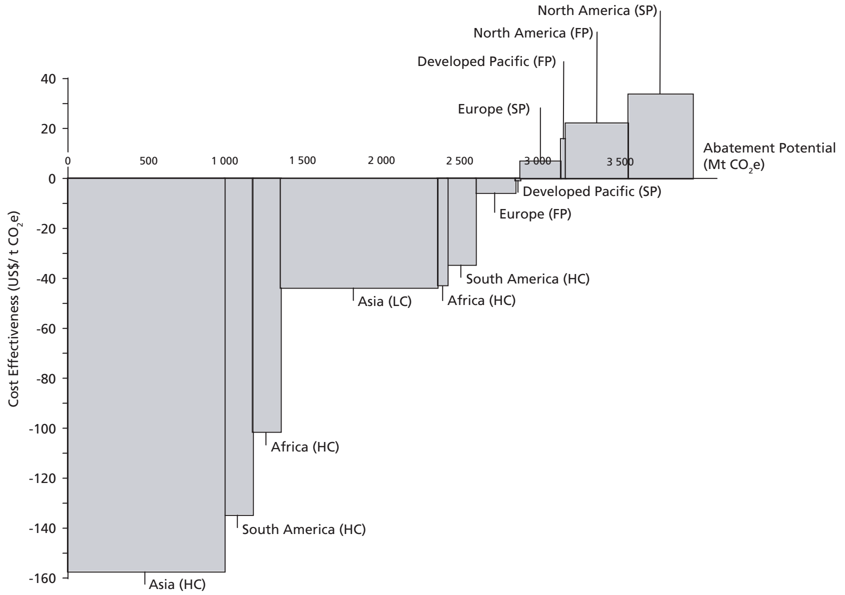


FIGURE 28: **Marginal abatement cost curve of a range of carbon abatement technologies and strategies for the world by 2030** *(Chapter XI)*

Source: modified from McKinsey & Company, 2009.

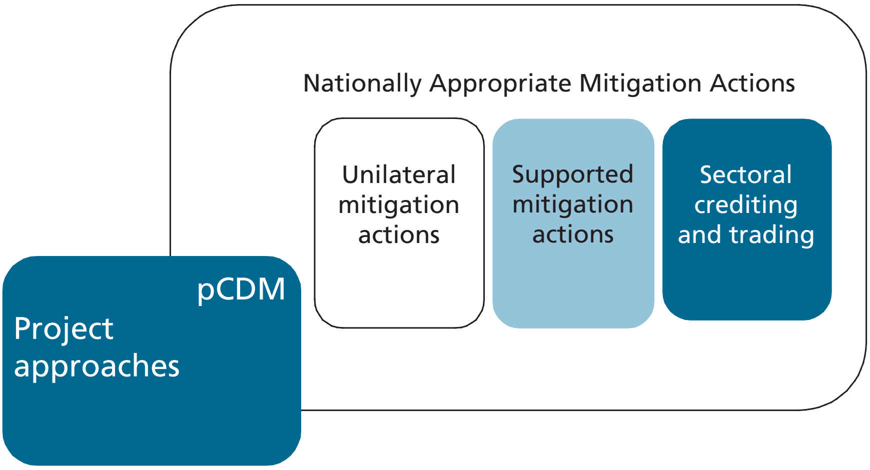


FIGURE 29: **Potential vehicles for carbon finance under future international agreements** *(Chapter XII)*

Grassland carbon sequestration: management, policy and economics

Grasslands are important worldwide and play a unique role as they link agriculture and environment and offer tangible solutions ranging from their contribution to mitigation of and adaptation to climate change, to improvement of land and ecosystem health and resilience, biological diversity and water cycles while serving as a basis for agricultural productivity and economic growth.

This book profiles 13 contributions by some of the world's most active scientists on the subjects of measuring soil carbon in grassland systems and sustainable grassland management practices. While many different aspects of carbon sequestration in grasslands are covered, many gaps in our knowledge are also revealed, and it is hoped that this book will promote discussion, prompt further research, contribute to develop global and national grassland strategies and contribute to sustainable production intensification.

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