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The applicability, efficacy and risks of natural sequence farming in the dryland agricultural zone of south west Western Australia

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Executive Summary

The Department of Primary Industries and Regional Development ("DPIRD") engaged The University of Western Australia ("UWA") to undertake a review encompassing the broader principles and practices of Natural Sequence Farming (NSF). The review has combined information available from the literature, relevant case studies, as well as outcomes and findings from interviews with knowledge holders and stakeholders to achieve the following objectives:

1. Develop a working definition and description of NSF as developed, described and documented by Peter Andrews and associates
2. Document the key principles and practices associated with NSF
3. Identify the expected benefits and associated risks with the application of NSF in the south west of Western Australia (SWWA) dryland agricultural zone, with a focus on broadacre wheat and sheep farming, and to summarise the hydrological and production benefits and risks, specifically addressing:
    a. The landscape component – floodplain and on hillslopes
    b. Landscape geomorphology (hydrology/hydrogeology) and how the risks and opportunities change across the hydrological zone transitions in SWWA
4. Design a landscape monitoring protocol to enable objective assessment of the performance of NSF as applied on any farm or catchment, including factors to consider about site assessment before implementation and related requirements.

Key Principles and Practices of Natural Sequence Farming

NSF is based on principles and work in the Hunter region of New South Wales by Mr Peter Andrews OAM. Elements of NSF share strong similarities with methods used by soil conservation authorities. NSF appears to have also modified and adapted these, but also includes methods not typically applied by these groups. The aim of NSF is to intervene in landscapes to rehydrate and increase water availability on hillslopes and recharge the alluvial aquifer, thereby reducing channel incision and soil erosion while promoting soil fertility and productivity. Within this, the three main components that constitute the framework of NSF are:

- Landscape rehydration by stepped diffusion via hillslope structures to retain water in the landscape for longer,
- Recreating a river morphology that allows water to cascade between steps created by leaky weirs and increased floodplain storage, and
- Limiting productive agriculture to 1/3 of the property while reducing grazing pressure to maximise vegetation cover, including by promoting weed growth.

Based on the main principles and objectives outlined in NSF literature, this review suggests that NSF can be summarised as:

Landscape remediation by manipulating the hydrology and geomorphology, with a focus on surface flow control structures to increase hillslope and river water retention, controlled grazing pressure and the use of weeds and exotic plants as colonising species to create novel ecosystems that maximise cover with the objective of addressing land degradation issues including channel and hillslope erosion, low floodplain productivity, salinity, overgrazing, loss of biodiversity, drought-intolerance, and infertile soils.

This an expanded version of the summary report on NSF from ARC Linkage project LP0455080, which more succinctly defined it as "*a sequence of flow control / bed stabilisation structures within the stream. NSF included limited stock grazing and revegetation with exotics and natural regeneration of plants.*" (Bush, 2010, p.3)

This review found that numerous NSF principles are not supported by published and peer-reviewed scientific understanding, with a range of concepts used or presented in ways that are unclear or directly contradictory. Key examples include:

- The NSF community frequently refer to a "chain of ponds" river morphology but provide examples which are not consistent with how this very specific river type is defined in the literature.
- The "chain of ponds" river morphology is found in very specific landscape settings and is not naturally found within most landscapes (particularly not in southwestern Australia).
- NSF advocates for water retention and recharge of alluvial aquifers suggesting that a freshwater lens will form over the top of saline water. There is no published data or expert opinion (from outside the NSF community) that a freshwater lens develops by alluvial recharge through a density stratification mechanism in SWWA. Published literature and expert opinion from SWWA aligns with the expert scientific review of NSF methods in the Hunter region, that this mechanism will likely result in elevated water tables and exacerbate land degradation from salinity. This approach, if applied in the low gradient and saline lower rainfall areas of the SWWA, will likely result in increased land degradation from salinity.
- The economics of lost production from surface water management structures combined with inefficiencies that structures pose to controlled-traffic GPS guidance, plus modern no-till practices combined with sand surface soils, means that NSF is in opposition to widespread trends in broadacre grain farming in SWWA in recent decades. These trends have typically been away from surface water management, with no-till and GPS farming combined with reduced rainfall quantity and intensity (due to a drying climate) meaning that surface water runoff has become less of an issue.
- The NSF approach to addressing salinity through landscape rehydration is at odds with expert opinion, peer review papers and reports from SWWA that identify benefits from using perennial vegetation to break the capillary linkage from salinity groundwater to ponded surface water (i.e. disconnecting rather than reconnecting surface and groundwater systems). The potentially beneficial component of NSF to addressing salinity is through introducing perennial vegetation in the landscape, which essentially dehydrates the landscape.
- Production benefits of NSF and landscape rehydration are promoted as increasing production by up to ten times despite farming activities (grain production and grazing) being confined to only one third of the farm area. There is, however, no evidence to support this claim and farming systems specialists and agronomists who were consulted have discredited this claim given the nature of the soils and rainfall in SWWA.
- The term "natural" in relation to NSF practices is not consistent with accepted definitions of naturalness. NSF directly promotes non-native species and the use of weeds, and therefore meets the definition of a "novel" or "remediated" (rather than natural or restored) ecosystem.

Risks and Opportunities

Revegetation of the landscape is one of the potential opportunities/benefits of NSF implementation in stream bed and bank stabilisation and provision of habitat in the riparian zone, and reduction of flow velocities and erosion on hillslopes and increasing land cover. Additionally, vegetation is a source of organic matter and some nutrients for the development of carbon-rich soil profiles. Revegetation of the landscape (where not associated with earthworks structures) may also work to sufficiently de-couple the capillary fringe from the surface and break the cycle of inundation and exfiltration of salts in the soil profile. Mulching, which is heavily promoted by NSF, has been associated with the benefits of evaporation suppression and reducing salinity risks. NSF does, however, emphasise the use of fast-growing, exotic species including willow (*Salicaceae)*, and references species listed as Declared Pests within the Western Australian Organism List (WAOL). Work in New South Wales has suggested that native species like the river oak (*Casuarina cunninghamiana*) be used in non-saline areas, and work in south western Australia identified the role of Sheoak (*Allocasuarina*) and paperbark (*Melaleuca*) as a colonising species. In addition to maximising vegetation in the landscape, NSF also advocates for reduced grazing pressure which has the benefit of increasing ground cover and protecting soil from erosion by wind and raindrop impacts.

A factor likely to serve as a barrier to NSF adoption in SWWA is the trend in broadacre farming away from engineering and earthmoving surface water structures. This has included the removal of legacy surface water management infrastructure to facilitate improved equipment movement, controlled traffic farming to address soil compaction, and returning land to production. This has been driven by the need for increased efficiency to remain competitive but also a drying climate and reduced surface water runoff, and a lack of large flood events in the last two decades. One attribute of the changing climate is the transition to higher-intensity summer rainfall where surface water interventions may be feasible and desirable. However, a key issue identified in this review is the limited capacity, capability and cost to seek expertise to plan, design, supervise and build appropriate water management structures that are fit for purpose and can be integrated with production systems and sustained in extreme events. Prior work on WISALTS banks has shown that for growers, the costs associated with lost production because of the construction of contour banks was a greater cost than those arising directly from earthworks construction. These factors represent a significant barrier to the implementation and economics of NSF.

The viability of NSF as an agricultural farming system can be considered in relation to the area of property lost to production due to structures, and the ‘thirds rule’ proposed by Peter Andrews. Andrews proposed that the NSF interventions in the landscape will boost productivity by around ten times (related to structures that hold the soil at field capacity) whilst allowing for production on only 1/3 of the land. NSF proposes that the other 2/3 of the land on hillslopes and riparian areas are removed from production, such as grain growing or pasture for grazing. No published literature could be found that supports an increase in productivity of this magnitude (ten times) from NSF interventions, and conventional farming systems experts considered this scale of productivity increase to be unrealistic for the climate and soils of southwestern Australia. The mechanisms proposed by NSF for nutrient retention and cycling, fertility and natural soil health are also unlikely to be associated with enhanced production benefits, especially over the longer-term as the legacy fertiliser bank is depleted.

Based on the review, there is little evidence to suggest that NSF is a viable farming system for broadacre cropping systems, when adopted as proposed by Peter Andrews. Where profit and efficiency are not the key drivers of farming operations, NSF may offer solutions for people who have other objectives in their operations. There are also examples of landholders who have adapted the ideas of Peter Andrews, which is unsurprising, given that NSF itself appears to have incorporated and adapted aspects of conventional soil conservation approaches. The NSF community also identified that conventional farming systems do not necessarily include the external and indirect costs (such as off-site chemical impacts or high-nutrient runoff) that may degrade other systems, and argue that any holistic assessment of NSF should consider all internal and external factors in assessing viability, cost and impact of any farming system.

For most of the landscape hydrological zones (hydrozones) within southwestern Australia considered in this review, NSF methods are generally considered to potentially reduce adverse risk ratings for wind erosion, soil compaction and soil organic carbon, and to a lesser extent soil acidity. However, as related to dryland salinity, NSF interventions in most hydrozones are considered likely to exacerbate current salinity risk across SWWA. The impact on water erosion was assessed as depending on site-specific factors such as the scale, design and quality of construction for flow control structures on hillslopes and in-channel leaky weirs. Increased ground cover will likely improve the land condition in relation to raindrop impact and related water erosion.

Application of NSF in the SWWA

Using the CSIRO expert panel and ARC Linkage reports from New South Wales, combined with case studies and interviews with NSF proponents, plus experts in hydrology, geomorphology and farming systems, NSF is suggested as being suitable or applicable for the following areas:

- The rejuvenated and steeply sloped catchments near the Darling Scarp of the Avon Basin (e.g. Toodyay, Northam, York areas)
- Areas of the Chapman Valley (Sugarloaf System)
- The higher rainfall and hydrologically connected catchments draining to the coast from Perth to Esperance (the south west and south coastal areas of WA)
- Limited areas of sandplain systems in the Swan Coastal Plain and Perth Basin with no salinity risk
- Applied with caution in sandplain systems in the medium rainfall zone with no present surface salinity issues (e.g. Meckering & Wongan Hills area), and on skeletal soils in rejuvenated systems where rainfall is above 350 mm, and some similar land systems along the south coast.

These landscapes can be summarised as the dissected and low-salinity higher rainfall (>600 mm zone), some medium rainfall areas (>350mm) that have higher gradient and more connected or dissected/rejuvenated systems proximal to the coastal fringe of SWWA, and well-drained sandplain systems that contain localised and fresh to brackish groundwater systems that present a low risk to the development of secondary salinity.

Case studies where NSF or NSF-like farming operations have been used are most commonly associated with smaller-scale primary production such as niche livestock production, equestrian businesses or smaller-scale operations supported from off-farm income or other financial support or subsidy. Widespread implementation of NSF principles across the broadacre cropping and mixed grazing-cropping farming systems of the grainbelt of SWWA is considered unlikely due to the following factors:

- Economics: the restrictions placed on areas lost to earthworks, and production on only 1/3 of farmland area for productive agriculture makes most farming businesses unviable. A notable trend in broadacre agriculture in SWWA has been the movement away from livestock and therefore, the value placed on perennials for livestock is of limited benefit to cropping-only operations.
- Efficiency: trends have been away from earthworks to tillage, such that growers have remained locally and globally competitive from more efficient farming practices, and this has included large paddocks and automated machinery with GPS controlled traffic, where within-paddock structures (such as NSF flow structures) hinder efficient farm machinery operation, and legacy water engineering structures have been filled in.
- Environment: A key transition with the drying climate in SWWA combined with no-till practices has been the reduction in surface water runoff issues that require engineering structures. The lack of extreme rainfall-runoff events for the last two decades means that surface water engineering is not considered an important component of current inland, grainbelt farming systems. Previous work addressing salinity and production limitations has focused on shallow watertables and waterlogging, which are all excess water issues. Adapting landscape rehydration methods from a very specific landscape setting in NSW, is at odds with the valley floor saturation issues and land degradation from salinity challenges facing growers across the grainbelt of SWWA. Promoting landscape rehydration to address salinity (a water-excess problem) lacks credibility.
- Experimental Data and Experiences: Experimental data, scientific understanding and experiences within the WA wheatbelt is that dehydration of the landscape using revegetation of saltland, disconnecting the saline groundwater from the surface, and preventing waterlogging in saline landscapes are methods to address salinity and lost production. There are serious reputational risks to DPIRD in promoting NSF methods of ponding water and landscape rehydration which are known to cause land degradation by salinity (based on decades of research by DPIRD and other organisations). There are also legacy experiences within the WA farming community from limited benefits that came from interventions such as WISALTS banks in the 1970s and 80s, and deep drainage in the 1990s and 2000s, methods which failed to address salinity.

Monitoring and Recommendations

A key finding of the review and a theme from interviews is the lack of empirical data, to move beyond desktop assessment. Care needs to be exercised in committing to any monitoring program, given the significant times, costs and logistics outlined below. A clear definition of the question(s) being answered, and a review of prior knowledge and the conceptual basis of the question or hypothesis should be undertaken before committing to the type of extensive and expensive monitoring program that would be required. There exists a body of prior scientific knowledge, empirical data and lived experience (including what is captured within this review) to already resolve many aspects of these questions.

If there is a desire to resolve identified knowledge gaps, raw data from well-designed studies will be needed. Any monitoring and evaluation program designed to collect new data would need to:

- Implement a best practice trial design, ideally with a NSF intervention at one location, paired to a (near) identical control site at a proximal location, and baseline monitoring for several years before any intervention.

- Monitoring of the NSF intervention needs to be for a duration that is informed by the type of processes that are being evaluated and the timeframe over which these variables are known to respond to land management practices. This is suggested as a minimum of 5 to 10 years (post-intervention and after a pre-intervention baseline monitoring period). Some factors are known to respond at the longer timescales of decades or to individual events rather than being time dependent.
- The duration of monitoring also needs to consider that an objective of NSF is to make the landscape more resilient to events such as floods and droughts, and the monitoring period must include these events.
- Any monitoring program needs to consider the hydrozone or landscape context and recognise that findings from one landscape or hydrozone are not necessarily transferrable to another landscape setting or hydrozone, even within SWWA.
- The variables to monitor should be informed by the literature around NSF and the factors that it seeks to influence, but likely include:
    - Groundwater level and quality (especially salinity) and specifically test the applicability of the aquifer recharge groundwater density stratification hypothesis that NSF advocates whereby freshwater will sit atop saltwater within groundwater systems.
    - Assess surface water and soil moisture status, including hillslope and flow quantity and quality within river systems to address questions on landscape rehydration and increased recharge.
    - Monitoring patterns of river geomorphology, river type and sediment dynamics.
    - Assess groundwater salinity and soil salt accumulation.
    - Soil health and fertility, including the mulching and redistribution methods proposed by NSF and the role of residual or legacy fertiliser inputs.
    - Ecological and farming fodder productivity surveys of pasture/vegetation to monitor crop/production and pasture cover, health, productivity, and biomass.
    - Full agronomic assessment of the farming systems inputs, outputs, and profitability.
- There is potential for testing components of the limited number of NSF ideas that may contribute to addressing salinity and other land degradation issues based on the current scientific understanding in SWWA. For example:
    - Understanding how vegetation cover restricts direct evaporation and surface concentration of salts.
    - Investigating the potential for sediment trapped by leaky weirs and other structures to act as a mulch or cover that suppresses evaporation and surface salt concentration.
    - Investigating the potential for NSF and landscape rehydration to flush soils of low salinity, well-drained and high-transmissivity soils such as undulating sandy coastal settings.

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Ethical Declaration

Interviews with knowledge holders were conducted as part of this review, approved under UWA Ethics RA/4/20/6390. As part of the ethics approval, interviewed persons are not individually identified or by their specific organisation. Notes were taken during interviews, but these have not been provided to any external agency or used for any future research. All copies of interview notes destroyed on acceptance of this report.

Disclaimer

1. Introduction

1.1. Purpose

Natural Sequence Farming (NSF) is attributed to Mr Peter Andrew OAM, from his work in the upper Hunter region of New South Wales. NSF is also widely practiced and advanced by other individuals and organisations. It is one approach or philosophy, but there is a broader shift by some growers to regenerative agriculture, which emphasises biological and ecological practices to build soil health to drive production, restoring landscape function and low-input farming. Many primary producers who would not consider themselves engaged in regenerative agriculture are also working and innovating to change farming practices and systems to address land degradation, production constraints, productivity, environmental stewardship, and on-farm profitability.

The Department of Primary Industries and Regional Development (“DPIRD”) engaged The University of Western Australia (“UWA”) to undertake a review encompassing the broader principles and practices of NSF (Chapters 2 and 3). This review has considered the available literature and information available from interventions and case studies in eastern Australia where NSF originated but is focused on applying this knowledge to the south western dryland agricultural zone of Western Australia (Chapters 4 and 5). Interviews with knowledge holders and stakeholders have also informed the review. The overall aim was to capture both the efficacy, expected benefits and potential risks of implementing the NSF methods in the SWWA dryland agricultural zone of Western Australia (Chapter 6). The review also considers factors relevant to monitoring NSF's interventions in the SWWA dryland agricultural zone of Western Australia (Chapter 7).

1.2. Objectives

The objectives of this review, defined by DPIRD, included:

- Developing a working definition and description of NSF as developed, described and documented by Peter Andrews and associates (see Chapters 2 and 3).
- Documenting the key principles and practices associated with NSF (see Chapters 3, 4 and 5).
- Identifying the expected benefits and associated risks with the application of NSF in the SWWA dryland agricultural zone of WA focusing on broadacre wheat and sheep farming, and to summarise the hydrological and production benefits and risks, specifically addressing:
    - The landscape component – floodplain and on hillslopes (see Chapter 6.1).
    - Landscape geomorphology (hydrology/hydrogeology) and how the risks and opportunities change across the hydrological zone transitions in SWWA (see Chapter 6.2).
- Designing a landscape monitoring protocol to enable objective assessment of the performance of NSF as applied on any farm or catchment, including factors to consider about site assessment before implementation and related requirements (see Chapter 7).

The scope of this review is specifically focused on the hydrological and production benefits and risks as related to the application of NSF as a specific form of regenerative agriculture and in the south-west dryland agricultural zone of Western Australia.

2. Background

The south west dryland agricultural zone of Western Australia (herein SWWA), is a landscape that reflects the changes since the European colonisation of Australia in the late 18th century and the conversion of woodland and forest into seasonal dryland agriculture (Bradshaw 2012). In southwestern Australia and elsewhere, this has allowed significant regional development opportunities. One impact of the agriculture production systems has included changes to catchment hydrology and subsequent impacts on farm productivity and profitability due to landscape degradation. Farmers have also faced significant challenges due to a cost-price squeeze from rising costs of inputs and declining commodity prices in real terms, exacerbated by land degradation pressures that impact productivity and profitability (McCown et al. 1992). These challenges have set the context for the broader regenerative agriculture and specific NSF approaches to farming and land management (Abbe and Brooks 2011).

2.1. Degradation of Agricultural Landscapes and Riverine Environments

The health and productivity of agricultural landscapes and rivers have been impacted by land degradation issues, including salinity, soil compaction, water repellence, soil acidity, depleted soil organic matter, accelerated soil erosion, and a loss of biodiversity in SWWA (Department of Agriculture and Food 2013; Wasson et al. 1998). Removal of vegetation increases the exposure of the landscape to wind and water erosion (Department of Primary Industries and Regional Development 2019) and also contributes to dryland salinity through a rising groundwater table that mobilises soluble salts (McFarlane et al. 1990; Raper et al. 2014). Other land-use practices, such as stubble burning, dry seeding and maintaining high stock numbers and over-grazing, unsustainable cropping practices, and land clearing, can also contribute to land degradation on farmland (Wasson et al. 1998).

Land degradation has impacted farmland productivity, with an estimated economic impact for 2007-2013 of $519 million per annum for issues surrounding dryland salinity alone (Department of Primary Industries and Regional Development 2019). These issues are not unique to any particular landscape within SWWA or to any specific farming systems approach. The risks and benefits from different land management and farming systems and their impact on land degradation are not homogenous through SWWA. There are risks and opportunities with any farming system. It is critical to understand these in the context of the underlying physical process and the landscape zone context.

2.2. Methods of Managing Degraded Landscapes

Landscapes and river systems are composed of the physical structure and stability of the catchment hillslopes and river, including the hydrology and underlying geology, biological inputs, chemical processes, and ecological values. These exist in a dynamic balance with inter-related feedback mechanisms required for the catchments and river system to function (Wohl et al. 2015b). Sediment and water input are the critical processes that create, maintain and modify river systems. The connection between system components is essential in controlling water and sediment movement through landscapes, combined with the boundary conditions including; riparian vegetation roughness, channel slope, valley width or confinement, and the channel substrate (Charlton 2007). Even small changes to any of these components can alter the form, structure and stability of catchments and hillslopes, broader floodplain zones and the in-channel structure and function of the active river channel, including associated geomorphic units, vegetation and habitat (Brierley et al. 1999). Human modification of catchments and river systems can disrupt the hydrological and biophysical processes, with significant implications for the viability and profitability of primary production and ecological diversity, habitat and broader ecosystem services (Wohl et al. 2015a).

Many methods are used to manage landscape degradation aimed at supporting increased productivity and profitability. Farming systems have embraced a transition from tillage to no-till farming (Department of Agriculture and Food 2013) and GPS controlled traffic paddock management. On a catchment scale, revegetation and reforestation have been considered to address water balance changes from land clearing for agriculture (Hatton and Nulsen 1999; Hatton et al. 2003). Integrated vegetation bands (IVBs) or alley farming have been proposed to also address water balance issues and for intercepting overland flows and reducing the risk associated with hillslope erosion and downstream sedimentation (Ryan et al. 2015). Engineering interventions to address the role of overland and throughflow, including grade banks and modified absorption banks (also WISALT banks) in the attempt to control salinity (Henschke 1989), while saltland pastures and other salt-tolerant species are advanced as solutions for saline valley floors (Barrett-Lennard et al. 2005). Regenerative, conventional, and indeed all growers are innovating, adapting, and experimenting with different farming systems and land management methods to remain competitive and globalised agricultural sector.

Land degradation is not a recent challenge to primary production, with the role of salinity and climate change recognised as pivotal in the decline of the Mesopotamian civilisation (Diamond 2004; Jacobsen and Adams 1958). Other landscape management and agricultural practices have focused on lower input systems and sustainable food and fibre production. Some producers have embraced a transition in whole or part towards organic farming systems that emphasise production without synthetic-based fertilisers and pesticides. Biodynamic farming has been around for a century, based on Rudolf Steiner's ideas that focus on the interrelated spiritual and ecological connection of soil, plants, animals, and people within a production system. The holistic grazing regime based on Allan Savory's work and applied in some Australian rangelands also emphasises the holistic relationships of land, people, animals and grasslands and the need to plan landscape use and adapt to changing environmental conditions. Other movements approach agriculture based on restoration of the complex balances which govern landscapes, including the water cycle, the solar cycle and soil health (Massy 2017). Haikai Tane and Wilhelm Ripl are also identified as influencing regenerative agriculture and NSF.

In summary, primary producers have been and continue to seek solutions to the challenges they face around increasing production costs relative to returns and reducing the natural capital that supports production. Their business relies on natural resources to sustain their livelihoods and production systems, but these face various degradation pressures. Many are also motivated by inter-generational equity principles and handing on land in better condition or addressing land degradation on their properties that can have beneficial on-site and off-site benefits to the environment. In this context, many potential solutions, philosophies, and approaches to address these challenges have emerged, including regenerative agriculture and NSF.

2.3. Origins of NSF

While this review is focused on NSF within SWWA, it is important to briefly recognise some similar practices and approaches that pre-date NSF and have influenced land management, particularly in relation to conservation earthworks. Many of the intervention methods used in NSF and other approaches have their origins in work of the Agriculture and Soil Conservation Departments within the United States (e.g. Tennessee Valley Authority and US Army Corps of Engineers) and State agencies within Australia. The work of Percival Yeomans and his Keylines approach (though developed in New South Wales (NSW)), as well as H.S. Whittington's WISALTS (Whittington Interceptor Salt Affected Land Treatment Society) banks, are significant in SWWA, as is the work of Ron Watkins in applying and adapting these approaches to his land in the Great Southern region of SWWA. These had a significant influence and are at times drawn upon as examples by practitioners, purveyors and purchasers of regenerative agriculture and NSF philosophies in SWWA. A brief overview of the Keyline and WISALTS approaches are detailed below, as elements of these methods are evident in the framework of Natural Sequence Farming (NSF).

Yeomans Keyline

Percival Yeomans developed the Keyline system in the 1950s to address soil degradation on his property, "Nevallan" in NSW (Massy 2017). By manipulating the topography and hydrology of the landscape to retain water higher on the hillslope, Yeomans sought to restore soil fertility, structure and depth of organic soil on his land (Yeomans 1954). The Keyline refers to a contour in a valley setting found by studying the way the land slopes, identifying where steeper slopes meet gentler downstream slopes. These areas as designated as "Keypoints" while the line that connects the Keypoints is known as the Keyline (Charles 1960). This Keyline is considered to be "the key to water movement in that area" (Monkhouse 1960) as water in ditches will move at right angles to the land, along the Keyline (Charles 1960). By considering the natural topography of the landscape, the Keyline approach was used to inform the placement of drains along Keylines and the construction of dams at Keypoints, enabling runoff from the landscape to be harvested and conserved (Yeomans 1954).

The Keyline approach is recognised in a Western Australian context at Ron Watkins' farm in the Frankland region of Western Australia. To combat salinity, Watkins constructed swales along the Keylines and then revegetated the swales. By retaining water on his property and improving soil fertility, Watkins claims that the Keyline approach increased land productivity and biodiversity (Massy 2017). The Keyline approach is consistent with the approaches of both regenerative agriculture and NSF in "rewetting" the landscape and retaining rainfall within hillslopes. Yeomans and the Keyline's principle are cited as influential on the principles that led to the development of permaculture agriculture.

WISALTS

WISALTS (Whittington Interceptor Salt Affected Land Treatment Society) banks were developed by H.S. Whittington and promoted through the WISALTS organisation formed in 1978 (Conacher et al. 1983a). These modified absorption banks were developed to suppress salinity by controlling and intercepting throughflow and surface runoff (Conacher et al. 1983a; Henschke 1989). This was done by constructing clay-lined banks on the level or slight grade to prevent water seepage through the banks.

A monitoring program at Dangin, WA concluded that WISALTS banks effectively prevented soil erosion and reduced flooding and waterlogging on low-lying land but were ineffective at intercepting the deeper groundwater system, which was the sole contributor of salt to the streamline (Henschke and Bessell-Browne 1983). Additionally, Henschke and Bessel-Brown (1983) found that the WISALTS banks were subject to leakage both laterally and vertically, contributing to groundwater recharge. Leakages were attributed to incorrect construction of the interceptor or sub-optimal soil conditions, leading to cracking and increased permeability (Conacher et al. 1983b). McFarlane et al. (1990) found that WISALTS banks worsened salinity by recharge of the underlying saline groundwater with freshwater, with these findings supported by Conacher et al. (1983a), who showed that there had been a minimal improvement to salt-impacted land where WISALTS had been implemented (Conacher et al. 1983a). Henschke and Bessel-Brown (1983) concluded that *"WISALTS banks could be considered for some particular situations…but are not believed to provide any advantage over the standard recommendations for general treatment of slopes above saltland."*

2.4. Natural Sequence Farming

Natural Sequence Farming (NSF) is attributed as being developed by Mr Peter Andrews OAM, since the 1970s (Norris and Andrews 2010). It has been popularised since the 2000s as a method of managing and restoring degraded landscapes. Andrews demonstrated the principles of NSF on his 1190 hectare property, Tarwyn Park, in the Upper Bylong Valley in New South Wales (Andrews 2006). Before implementation of NSF practices, Andrews described the property as severely degraded, with surface salting evident on the floodplain, degraded soils, and an eroded stream channel (Andrews 2006; Tane 2006). In response, he developed a model for managing the landscape. He credits this as reflecting conditions before any disturbance of the catchment (Andrews et al. 2005). The focus of NSF is the retention of water in the landscape via interventions to create a system referred to as "stepped diffusion broadacre hydroponics" (Tane 2006). Grazing pressure was reduced, and promotion of all vegetation cover types was encouraged (including weeds). He also implemented zoned management of the landscape that sought to promote a more closed system of biogeochemical cycling as the basis to restore natural processes conducive to productive farming (Newell and Reynolds 2005; Young et al. 2002).

The method gained much public attention and traction following an ABC television program *Australian Story* on NSF in 2005, and the publication of Andrews' book entitled "Back from the Brink" (Dobes et al. 2013). The ABC has aired subsequent *Australian Story* shows on NSF, and the application of NSF has continued to gain public attention through its application on various farming estates across Australia, including the Baramul Stud owned by businessman Gerry Harvey, and the collaboration of Peter Andrews with the late Tony Coote on latter's Mulloon Creek property that led to the formation of the Mulloon Institute. Within Western Australia, *Australian Story* featured three programs in 2012, 2014 and 2017 that followed David and Frances Pollock's work applying NSF principles on their property, Wooleen Station, in the semi-arid Murchison River rangelands.

NSF principles continue to be further popularised and politicised, such as the visit of Prime Minister Scott Morrison and Deputy Prime Minister Michael McCormack to the Mulloon Creek property prior to the National Drought Summit in 2018. NSF continues to be promoted by Peter Andrews through his website (http://www.peterandrewsoam.com/), and his son Stuart Andrews through his Tarwyn Park Training organisation (https://www.tarwynparktraining.com.au/). Work through the bequeathed estate of Tony and Toni Coote and the Mulloon Creek Natural Farm demonstration project and work of the Mulloon Institute (https://themullooninstitute.org/) promotes NSF approaches to the management of the Australian landscape. Peter Andrews and some of these collaborators are also involved in The Australian Landscape Science (TALS) Institute Limited (https://www.tals.org.au/) which promotes, lobbies and provides training in NSF methods with input from Peter Andrews. The property "Yanget" in the Chapman Valley of Western Australia is a key case study demonstration site promoted by TALS and NSF proponents within WA and Australia. There are several practitioners of the NSF techniques and broader regenerative agriculture practices that incorporate these philosophies in whole or in part, including within SWWA.

It should also be noted that there are a large number of other groups and individuals who have worked for many decades across the for-profit and not-for-profit sectors engaged with individual landholders in planning, designing and implementing works to address the same challenges of land degradation, landscape rehabilitation, increasing perennial vegetation within the landscape. This includes Natural Resource Management Organisations (NRMOs) such as South West Catchment Council (SWCC), Northern Agricultural Catchments Council (NACC), South Coast NRM, Wheatbelt NRM and Perth NRM. They are engaged through southwestern Australia and provide strategic leadership and on-ground action. State Government agencies across agriculture (currently DPIRD), water resources (currently Department of Water and Environmental Regulation, DWER), and biodiversity (currently Department of Biodiversity, Conservation and Attractions, DBCA) also have a long history of working with landowners to address land degradation issues. The Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Universities have been active research contributors to advancing evidence-based knowledge in farming systems, regenerative agriculture and tackling land degradation. Various farm planning, agronomy and consultancy companies have also promoted conventional and regenerative practices within SWWA to address the same issues.

What is NSF specifically?

Within Chapter 3 of the review, we use the available resources in a hierarchy from published peer-review articles, peer-review reports and studies, books, then websites and other written non-peer review information. Information from knowledge-holder and stakeholder interviews was also used to refine and inform the review of NSF. A great challenge is that there is a lack of published data and information, NSF lacks specific technical detail and documentation, and there are some differing opinions on what the objectives of NSF are. Some of the information is directly contradictory. Different people and groups involved in NSF or the broader agriculture sector do not necessarily have the same definition of what it is specifically, how the methods should be applied, the objectives of NSF, and opinions on anecdotal experiences of the success or failures of various techniques.

Based on a synthesis of available information, NSF can broadly be summarised as a land management technique that seeks to improve soil health, reinstate native plant communities, restore the health of floodplains and streambeds (Newell and Reynolds 2005), and increase groundwater storage in the hillslope soils and floodplain aquifer (Williams 2010) through harnessing natural processes and implementing various physical interventions. From within the NSF advocate community, TALS characterise it as a landscape restoration and farming system. They highlight the terminology of Prof Haikai Tane who describes this type of approach as implementing regenerative farming systems that are based on the foundational principle of creating a "stepped diffusion system of broadacre hydroponics" (Tane 2006).

The philosophy underpinning NSF based on the work published by Peter Andrews, can be summarised as:

- Water is central and the over-riding factor in any landscape

- Interventions should aim to slowly step water through the landscape and retain water in the landscape, ideally maintaining soils at field capacity
- The top third of the landscape should be protected with ground cover (including weeds) to reduce erosion
- The bottom third of the landscape should be protected with ground cover to trap any sediment and nutrients and stepped in-river structures (leaky weirs) that slow water and promote alluvial aquifer recharge. Mulching of the vegetation allows the return of harvested materials to the top of the landscape, creating a closed system and maximising productivity and soil fertility
- Production is recommended to occur in the middle third of the landscape. Soils are held close to or at field capacity by diffusion of water from higher in the landscape and natural fertility methods boost productivity, allowing a sustainable, profitable, and sustainable farming system.

An expert panel (Young et al. 2002) considered the NSF methods applied at Tarwyn Park (NSW) to be partially successful in yielding increased productivity in some areas but concluded that there were limitations regarding the widespread applicability of NSF in accordance with hydrogeological and hydrological constraints. The summary report on ARC Linkage project LP0455080 (see Chapter 5 for a summary of the report) included evaluating NSF intervention work on Gerry Harvey's Baramul Stud in the Widden Valley (NSW). It concluded that native plants such as Casuarina were more effective than weeds or willows promoted by NSF. They found that the greatest productivity benefits came from controlling the grazing pressure (which would not necessarily translate to total farm profitability, see Bush, 2010). They found that the intervention of flow structures within water courses that is a feature of NSF provided benefits in some reaches but posed a significant risk to salinity where they intersected sediment with a high salt store. They concluded that "*NSF is most suited to areas dominated by local fresh ground water systems in highly transmissive floodplain sediments. The main consideration is the size of the stream and floodplain system. Small upper catchment streams and gully systems are best suited to the NSF approach*. (Bush, 2010, p.3)

There may be risks and opportunities associated with NSF's specific practices due to how the methods of NSF are transposed from one landscape to another. These hydrogeological and hydrological factors need consideration and guidance within the landscape of SWWA. Given the variability in landscapes and the current status of land degradation pressures across SWWA, it is likely that NSF may not have a single specific risk and opportunity profile at the scale of the entire southwestern dryland agricultural zone. The review, therefore, seeks to understand what NSF is (Chapter 3) and uses available case studies (Chapter 4 and 5) to understand the various interventions and processes. We then consider NSF risks and benefits in a SWWA landscape zone context that considers factors such as topography, soils, salinity, waterlogging, river geomorphology and related factors (Chapter 6). The review then considers factors that emerge from this work that could be used to inform any monitoring of the effectiveness and impacts of NSF (Chapter 7). Herein:

- **Chapter 3** presents a review of the defining methods of Natural Sequence Farming
- **Chapter 4** presents case studies from the literature
- **Chapter 5** provides a brief summary of the ARC Linkage Report relating to the implementation of NSF on Baramul Stud in the Widden valley

- **Chapter 6** collates this information into the context of SWWA to explore the risk and opportunity profiles associated with NSF
- **Chapter 7** presents a monitoring protocol for assessing the effectiveness and impacts of NSF
- **Chapter 8** is the conclusion of the review and provides guidance on monitoring the impacts and effectiveness of NSF

3. Key Principles and Practices of Natural Sequence Farming

For this review, Natural Sequence Farming (NSF) is defined as a land management approach based on the principles developed by Peter Andrews and applied since the 1970s. In defining NSF, the review has focused on the direct written material from Peter Andrews as the primary source. This focuses on the books “Back from the Brink” and “Beyond the Brink” which were developed from Peter Andrews’ ideas and then written into the books with the support of the author Philip Derriman. Other written resources are also drawn upon, and in places, the feedback from interviews is used to guide conclusions where there are conflicting views or uncertainty.

Foundational to Andrews’ NSF philosophy is the concept that landscapes operate and function according to a set of ‘natural sequences’. He refers to a ‘natural sequence’ as the complex interactions that exist in the natural environment – specifically, the interchange between the biological, ecological, pedological and hydrological factors. Andrews claims that European farming practices and even Aboriginal burning practices have disturbed these natural sequences and resulted in the large-scale land degradation observed across Australia (Andrews 2006). Some NSF advocates consider Eucalypt species as inappropriate for the Australian landscape due to being fire-prone and other characteristics, and instead favour less-flammable and deciduous species such as willow and poplar. NSF methods seek to reintroduce some of the natural landscape patterns and processes that had previously operated within the landscape and thus rehabilitate the degraded landscape, but the objective of NSF is not to return the landscapes to pre-European settlement condition (Dobes et al. 2013).

The working summary of NSF from ARC Linkage project LP0455080, defined it as “*a sequence of flow control/bed stabilisation structures within the stream. NSF included limited stock grazing and revegetation with exotics and natural regeneration of plants.*” (Bush, 2010, p.3)

NSF can be considered as a regenerative land management approach (Massy 2017) which primarily employs techniques on the hillslope to maximise water retention (landscape rehydration) and vegetation cover higher in the landscape, and uses structural interventions (referred to as leaky weirs and floodplain structures) within the riverine areas to manipulate the hydrological regime in favour of water retention and alluvial aquifer recharge (Andrews 2006). The written literature produced by Peter Andrews and associates refers in detail to the leaky weirs as replicating the specific ‘chain of ponds’ river geomorphology type (Andrews et al. 2005). The objective of these structures is to reinstate the natural channel-floodplain connectivity (Newell and Reynolds 2005) and increase groundwater storage in the floodplain aquifer (Williams 2010). Combined with non-structural interventions (such as revegetation and modified grazing patterns), these methods seek to address issues related to degradation of the landscape and to increase land productivity (Andrews et al. 2005). Some of the major land degradation issues that NSF specifically seeks to address include: channel and hillslope erosion, low floodplain productivity, salinity, overgrazing, loss of biodiversity, drought-intolerance, and infertile soils (Newell and Reynolds 2005).

Based on the review of available information, there are several components or principles that constitute the framework of NSF. These include measures to manipulate the hydrology, increase the fertility of the landscape and foster plant succession. These can be divided into three main categories (Table 1):

- Manipulate the Hydrology
- Revegetate the Landscape

- Restore Fertility

The conceptual underpinnings, the practical implementation and expected outcome for each of these principles is summarised in

Table 1 and further explored in sections 3.1-3.3.

Table 1: Principles and practices underpinning Natural Sequence Farming (NSF) land management

Principle	Major Concept	Practical Implementation	Desired Outcome(s)
Manipulate the Hydrology	Landscape rehydration on the hillslopes aligned with the aim of creating a stepped diffusion broadacre hydroponics land management system and chain-of-ponds river morphology within the valley floor and river channel to reduce water velocity, raise the water level and increase alluvial aquifer groundwater storage/recharge.	Grade control structures Contour (and reverse off-contour) banks Contour channels Cascading/stepped in-stream leaky weirs	Slow water movement and rehydrate the landscape Maintain soils at field capacity Increase soil moisture Reduce soil erosion Reduce channel incision Nutrient-rich floodplain Contain salinity
Revegetate the Landscape	Revegetation of the riparian zone (lowest 1/3 of the landscape) and hillslopes (highest 1/3 of the landscape) to slow water runoff/stream velocity and promote biodiversity.	Three-zone farm layout Revegetation of the hillslopes and riparian zone	Nutrient retention Reduce soil erosion/bank collapse Habitat provision Manage salinity
Restore Fertility	Retain fertility, slow the loss, and then filter and cycle fertility by capturing in lowest 1/3 of the landscape and cutting for mulch and returning to the upper 1/3 of the landscape. Fertility is held by boosting organic matter that improves the biological function of the soils, and the entire landscape, increasing productivity by ten times.	Mulch farming Modified grazing patterns Minimal cultivation on the floodplain	Cost savings Increase floodplain productivity

Many of the foundational principles of NSF are not necessarily new concepts. Reducing stream velocities to minimise the erosive impacts of water on the landscape is well studied and represented in literature. As Rutherford (2018) identifies, the use of grade control structures and rock-chutes to create leaky weirs has been applied within Australia and globally to combat river and gully incision and address issues by reducing river velocity, reducing downstream sediment impact, and retaining water to support vegetation recovery. Reducing grazing pressure and maximising vegetative cover is widely recognised as supporting reduced soil erosion, and mulching can suppress evaporation and loss of water from the soil surface. Stepped or terraced farming practices are used in many locations to control the loss of soil and to step or seep water through the landscape slowly.

Based on the available material produced by Peter Andrews and direct associates, there are three defining objectives of NSF that consistently appear across the available information and related to the three categories identified in Table 1:

1. Landscape rehydration by hillslope flow structures that retain water in the landscape for longer and slowly step or diffuse water across or down-gradient,
2. Recreating a ‘chain of ponds’ river morphology within the river system using leaky weirs and allowing water to cascade between steps (created by leaky weirs), and
3. Maximising vegetation cover, including by promoting weed growth.

NSF, naturalness and novel ecosystems

The published work of Andrews on the philosophical basis for NSF practices and objectives is hard to entirely reconcile with conventional scientific understanding and definitions of some of the key terms (e.g. “natural” or “naturalness”) that are used.

A specific example of this is the focus on what a natural sequence is, and the methods used to restore “naturalness” in the landscape by NSF. Within the scientific community, approaches such as using weeds and non-native species to achieve objectives are given terms such as functional mimics, remediation (rather than restoration), or producing novel (rather than natural) ecosystems. This is not necessarily a negative thing, and the scientific literature recognises that in some landscapes creating novel ecosystems or landscape remediation will optimise ecological, hydrological, and geomorphological outcomes (Rutherfurd 2000).

A novel ecosystem has surpassed an ecological threshold and can no longer be restored to its previous state (Collier and Devitt 2016). These ecosystems bear minimal similarity to present or historical ecological assemblages and have developed in response to anthropogenic disturbances or changes to the environment (Hobbs et al. 2009; Morse et al. 2014). As Morse et al. (2014) note, these novel ecosystems are not necessarily “bad”, but they do require active management. Three management approaches include: managing against a novel ecosystem, tolerating a novel ecosystem and managing a novel ecosystem (Truitt et al. 2015). The first approach, managing against a novel ecosystem, includes implementing measures that seek to restore the system to its historical state (“restoration”). However, this approach is generally not considered to be a viable management option due to the expense and complexity involved (Morse et al. 2014). Tolerating the novel ecosystem equates to inaction and is often the default management approach (due to insufficient funding or resourcing), but may be warranted in some instances or landscapes (Truitt et al. 2015). Managing novel ecosystems requires active management of the system and attempts to remediate (that is to “treat” or salvage) the system in its current state using a variety of methods, including the introduction of invasive species (as opposed to restoring it to its historical state or simply tolerating the change). The approach of NSF and the work of Andrews is closely aligned to the academic definitions of creating and actively managing novel ecosystems. NSF advocates for restoring physical aspects of a historical system, through the introduction of invasive weed species such as willows and blackberries.

NSF refers to the optimal arrangement of a river being a chain of ponds river type. River geomorphologists refer to a chain of ponds morphology as having a very specific meaning, recognised as occurring naturally in very limited and very specific geography with particular processes of formation and maintenance (Williams and Fryirs 2020). This strict definition of the morphology is not consistent with the leaky weir morphology advocated by NSF. Similarly, willows have been found to alter river geomorphology relative to reaches with native tree species, in favour of increased width and streambank erosion due to blockage (Pope et al. 2007), and adverse in-stream ecological effects (Greenwood et al. 2004; Read and Barmuta 1999).

The written work and available information on NSF, advocate directly for implementing chain of ponds morphology in all landscapes and the use of weeds to achieve objectives. This is a message that has been popularised by Peter Andrews, NSF advocates including TALS, the Mulloon Institute, the media and by politicians. When Deputy Prime Minister Michael McCormack visited the Mulloon Creek site in 2018, he reportedly declared that NSF is a "*model for everyone … this needs to be replicated right around our nation*" (Rutherford 2018). A key tenet of the NSF philosophy is that water (and by extension soils held at field capacity) is the primary control of production within a landscape and that this is applicable in all landscapes across Australia. The chain of ponds morphology is indeed a highly organic system that is at or around field capacity much of the time, however, the application of this across all landscapes in Australia is where mainstream river geomorphology and NSF diverge significantly:

- NSF is based on a view that there is a single optimal state of all landscapes where water is retained, creating a broadacre stepped diffusion hydroponics system (such as in a chain of ponds system).
- Conventional geomorphology views rivers and waterways as unique within their landscape context, comprising a range and continuum of morphological forms related to water and sediment supply and specific boundary conditions (slope, substrate, width and vegetation) imposed by their position in the landscape.

Defining NSF as articulated by Peter Andrews in scientifically accurate terms, NSF could be summarised as: *"landscape remediation by manipulation of hydrology and geomorphology focused on using flow control structures to increase hillslope and river water retention, controlled grazing pressure and the use of weeds and exotic plants as colonising species to create novel ecosystems that maximise cover with the objective of addressing land degradation issues including channel and hillslope erosion, low floodplain productivity, salinity, overgrazing, loss of biodiversity, drought-intolerance, and infertile soils".*

The summary of the ARC Linkage project LP0455080 (Bush 2010) could be adapted as a more succinct definition: *a sequence of flow control and bed stabilisation structures within the stream, limited stock grazing and revegetation with exotics to promote natural regeneration of plants.*

This review seeks to understand the specific approach and objectives of NSF in greater detail and then consider the potential risks and opportunities from the implementation and adoption of these principles across the various landscapes in SWWA. While it is understood that the 'natural systems' may vary between landscapes, proponents of NSF claim that the foundational principles are applicable across the Australian landscape. It is therefore important to understand in detail what these foundational interventions of NSF are, the associated landscape and process context and to use this as the basis to evaluate applying these methods in SWWA.

3.1. Landscape Rehydration and Manipulation of Surface Hydrology

One objective of NSF is to address land degradation by manipulating the hydrology of the landscape with the aim of making it more resilient to drought. Andrews and others refer to this as "rehydrating the landscape" or helping the landscape to function as a stepped diffusion broadacre hydroponics system. This is achieved through interventions to retain more water on the hillslopes that slow and retain water. Within the valley floor, the aim is to enhance hydrological connectivity between ephemeral floodplain channels, the broader floodplain, the main surficial stream flow channel and the alluvial groundwater aquifer (Keene et al. 2007). The specific interventions are overland flow intervention structures built on or slightly off the contour on hillslopes to encourage infiltration and water retention off the valley floor and are sometimes associated with tree planting (to form Integrated Vegetation Bands or IVBs). Within the river valley, structural measures such as rock, concrete or large woody debris (LWD) are used to block and impede flow by constructing what Andrews et al. (2005) refer to as leaky weirs. These leaky weirs create a pool geomorphic habitat, which creates what they refer to as the ‘chain of ponds’ river type. Weeds and other elements such as rocks increase riparian roughness as well as reducing flow velocities and controlling erosion and sedimentation. This increases river stage during higher flows and enhances recharge of the alluvial aquifer.

Hillslope landscape rehydration

Banks constructed on hillslopes, the floodplain and at the hillslope-floodplain break are used to collect, slow and store surface and subsurface flows from the hillslopes. Andrews (2005) emphasises the role of these features in preventing salts from reaching the floodplain aquifer. The collected water is retained within the structure until it is either lost by evaporation, flushed out by high floods (Young et al. 2002), or through leakage as a linear source of recharge. This is associated with the belief that the structures also boost organic matter, allowing soils to be retained at field capacity and boosting productivity.

The approach of NSF in constructing contour banks shares some similarities with Percival Yeoman’s Keylines approach. Banks used in the Yeoman system are used to harvest and store water in dams for later use (often higher in the landscape and on broad crests. The WISALTS system aims to distribute water across contours that is then stored for use or recharged into groundwater. By contrast, NSF is aimed at storing water in the soil, diffused across the landscape. The aim of NSF is to hold soils close to or at field capacity for as long as possible, over the largest area as possible. Additionally, proponents of NSF consider that where NSF seeks to restore the natural water system in the landscape, the Keylines concept developed by Percival Yeomans disrupts these systems (see Natural Sequence Farming: Frequently Asked Questions). There is a lack of written material that addresses the design criteria for NSF water intervention earthworks, which outlines the design specification, placement, purpose or principles. Proponents of NSF and those who have attended training sessions on NSF, including those run by Peter Andrews, talk about this as being informed by reading the landscape and deep knowledge of the natural sequences and processes, but the exact principles and design criteria for earthworks structures are based on anecdotal descriptions during oral training.

NSF and recreating the chain of ponds

Creating a river morphology that retains water in the riparian landscape and cascades or steps water along river channel is a key objective of NSF. Material written by Andrews and others refers to this as creating or even restoring a “chain of ponds”, and advocates the application of the approach across all landscapes (irrespective of whether the specific chain of ponds morphology is naturally found in that landscape).

Rutherford (2018) discussed the approaches of NSF and relates this to widely applied techniques in soil and river conservation and rehabilitation since the 1970s, typically termed as “grade control structures”, or rock chutes. These structures are also referred to as leaky weirs and can also be achieved by using large woody debris (LWD) to create dense logjams. These are used to control erosion by creating a pool environment to trap sediments and a stepped run habitat through the leaky rock chute weir or step in water elevation through the flow obstruction. This type of river morphology does not fit the definition of a chain of ponds (Williams and Fryirs 2020).

The aim of mimicking a chain of ponds morphology through constructing leaky weirs and adding channel roughness is integral to NSF's principles and objectives. Here we provide a review of the characteristics that define a chain of ponds river model within the scientific literature, such that NSF can be considered in this context.

Within the geomorphic literature, a chain of ponds is a very specific type of river. The planform is characterised by disconnected ponds and discontinuous watercourses found in low-gradient valleys, typically higher in the landscape. The valleys contain alluvial fill material that are highly stable and have vertically accreted over the last few thousand years (Mould and Fryirs 2017; Williams and Fryirs 2020; Zierholz et al. 2001) (also see Figure 1 from Fryirs and Brierley 2013). The term ‘swampy meadow’ and chain of ponds are often used interchangeably (Mactaggart et al. 2007). The term ‘swampy meadow’ best describes discontinuous channels in low-energy valley-fill environments. The chain of ponds most accurately represents watercourses that comprise a series of irregularly spaced ponds on a densely vegetated alluvial flat (Williams and Fryirs 2020).

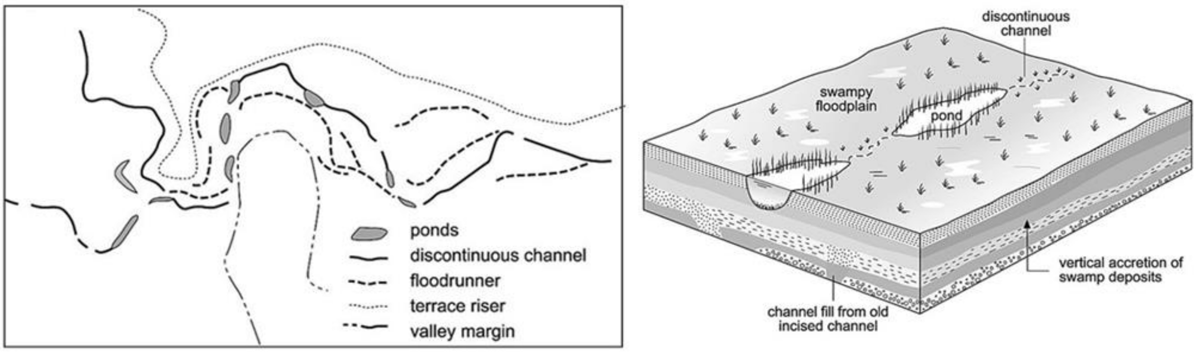


Figure 1: Example of the Chain of Ponds river type. A planform view (left) and cross-section schematic (right) of the chain of ponds river morphology highlighting the role of infill and vertical accretion processes within an unconfined upland river valley setting that defines the discontinuous channels and disconnected ponds that define this the chain of ponds morphology. From Fryirs and Brierley (2013).

The literature identifies that the term ‘chain of ponds’ has been incorrectly used or adapted to describe disconnected pools contained within an incised (continuous) river channel system (Scott 2001). The specific type of river geomorphic habitat created by NSF does not fit the accepted definition of a chain of ponds geomorphic river type. A chain of ponds river type would be defined by, and look like, a series of disconnected ponds that are connected by preferential flow paths that are approximately three times smaller than the width of the pond itself (Williams and Fryirs 2020), and which are fully connected during the overbank stage but disconnected during low-flow stages (Mould and Fryirs 2017). An example of a large-scale chain of ponds systems is provided in Figure 2 (Williams and Fryirs 2020).

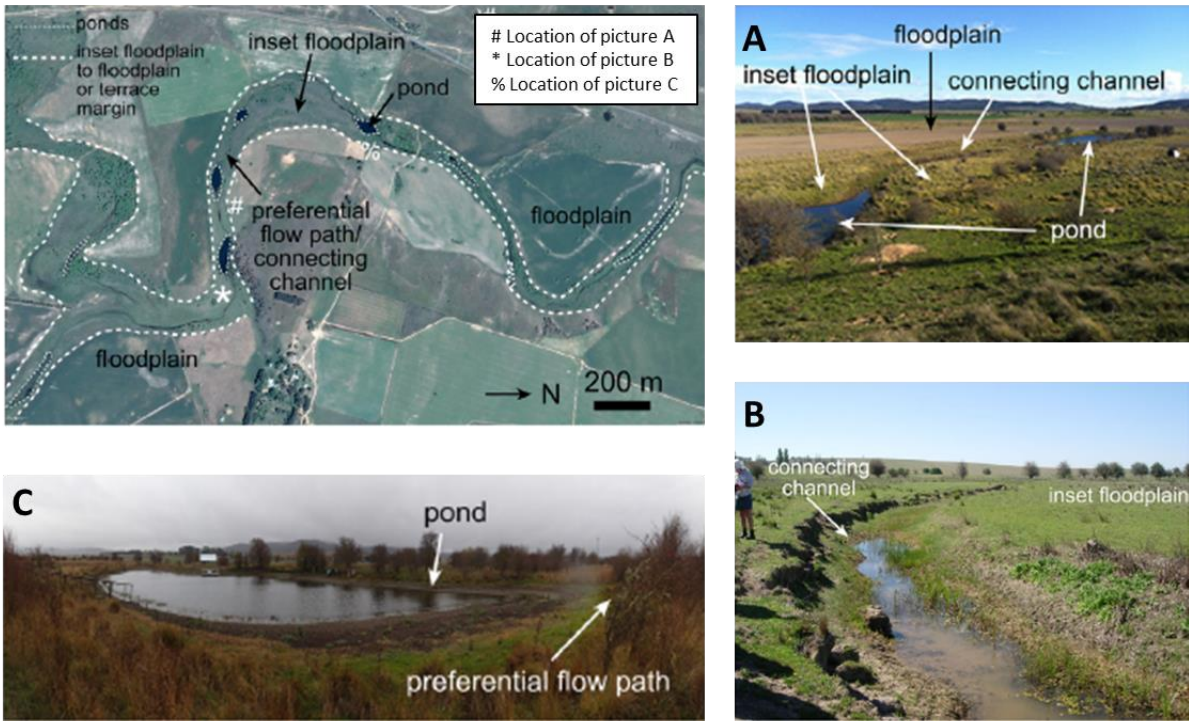


Figure 2: Geomorphic characteristics of large-scale chains-of-ponds. An example, A: Large-scale chain of ponds within the Mulwaree Ponds system. B: Connecting channel with an incised preferential flow path. C: Large-scale chain of ponds at the Crisp's Creek and headwater tributary chain of ponds in the Mulwaree catchment. Adapted from Williams & Fryirs (2020).

The disconnected, stepped-landform configuration of the chain of ponds river system establishes a low-flow buffered stream environment where under a pre-grazing agriculture land use, erosion and incision into the landscape is minimised and the system is in balance. This is supported by dating work on chain of ponds valley systems that show evidence of 1,500-3,700 years of vertical accretion, or the gradual vertical growth of the system by capturing sediments sources from rivers, lateral inflow from hillslopes and dust deposition (Mould and Fryirs 2017). The reduced flow velocities and anastomosing preferential flow paths enable surface water to be distributed across the low-energy floodplain (Mould and Fryirs 2017). Additionally, the greater residence time of surface water on the floodplain leads to recharge of the surficial alluvial aquifer enabling self-irrigation of the landscape to occur. Sediment retention by riparian vegetation enables aggradation to occur (Mactaggart et al. 2007) and also reduces the sediment load downstream (thereby improving water quality). Chain of ponds river types are often found in organic-rich peaty and swampy uplands with low-gradient meadows and can be dominated by grasslands and swampy meadows. The key boundary condition that controls the hydrology and sediment regime that defines the chain of ponds geomorphic type is likely governed more by the low-gradient, low-energy and swampy alluvial setting rather than a high-roughness environment.

The chain of ponds river system has become less prominent within the present-day. This is due to the effects of clearing vegetation, cattle grazing, and drainage of swampy meadows, which has led to destabilisation, incision and channelisation (Eyles 1977; Mould and Fryirs 2017). The flow-on effects of the degradation of the chain of ponds system is reflected in a landscape that is more susceptible to erosion and channel incision even during average rainfall events and low magnitude flooding (Zierholz et al. 2001). No longer zones of aggradation, these deeply incised chain of ponds and swamps have transitioned to source and transfer zones (Johnston and Brierley 2006).

In summary:

- Chain of ponds refers to a very specific type of geomorphology, and the term is widely misused, particularly within the NSF and regenerative agriculture communities.
- Chain of ponds refers to a very specific type of river type, characterised by:
    - A series of disconnected ponds
    - The ponds are connected by preferential flow paths that are significantly (less than three times) smaller than the width of the pond itself
    - The preferential flow paths are connected during the overbank stage and higher flows but are disconnected during low-flow stages
    - Set within a low-gradient alluvial valley and local aquifer system
    - A system that was a low-energy and vertically accreting before the introduction of European farming practices
- The type of channels being created through NSF practices and most examples presented by Peter Andrews and his NSF group and website, and Stuart Andrews and the Tarwyn Park Training group and the Mulloon Institute, do not fit the geomorphic definition of chain of ponds.
- Chain of ponds represents a geomorphic system that is closely aligned to the underlying philosophy of the system that NSF is trying to create across the whole landscape. It is a low-gradient, diffusive flow system that has high moisture content and highly productive organic soils. The chain of pond geomorphic type is only found in a relatively restricted area and forms under a particular set of controls, landscape setting, boundary conditions and flow regime.

What type of river geomorphology is NSF trying to create?

Based on the above review, the objective of NSF is not to specifically create a chain of ponds system in rivers, but rather to create a chain of ponds analogue everywhere in the landscape or wherever there is sufficient water. The underlying philosophy of NSF is related to this ideal of all landscapes optimally behaving as a broadacre stepped diffusion hydroponics system, of which the chain of ponds is a relatively unique geomorphic planform that has this characteristic. This may explain the adoption (and misuse) of this term within the NSF community.

The aims of NSF in creating a modified channel morphology in the landscape are achieved through the implementation of three main structural elements:

- The use of banks on the hillslopes to retain and diffuse water in the landscape,
- Construction of secondary diversion channels on the floodplain to distribute surface flow across the landscape, and
- Installation of in-stream grade control structures (leaky weirs) within the active river channel itself to reduce surface water flow velocity, promote sediment aggradation and facilitate recharge of the alluvial aquifer.

Within the riverine area, NSF can be most accurately described as adding functional habitat through leaky weirs to an existing river system of alternating pool and cascading fall structures with the aim of reducing flow velocity and trapping sediment or retarding gully and river bed incision. There is a focus on maximum vegetation roughness, including through the use of exotic species, and can also include the use of rock and rubble to add additional roughness and protection from channel incision. The aim is that water flows from one level to another with a plunge pool, meaning water falls into still water as a means of reducing erosion and stepping water along the river channel.

Floodplain - Secondary Diversion Channels

Structural control on floodplains through the construction of secondary diversion/contour channels within the valley floor to simulate pre-European multi-channelled floodplains is emphasised in NSF (Young et al. 2002). They propose that these anastomosing channels enable surface flow to be redistributed across the floodplain, thereby simulating chain of ponds-type river geomorphology by reconnecting streams to their floodplains via preferential floodpaths and irrigating the floodplains. The induced flow diversion also disperses sediment across the floodplain (Knighton and Nanson 2000).

River Channel - Grade Control Structures / 'Leaky Weirs'

NSF encourages grade control structures, also referred to as 'leaky weirs, to reduce stream velocity and reinstate stream-floodplain connectivity (Young et al. 2002), within the incised or active primary flow channel. The weir (Figure 3) is constructed by adding boulders and debris to the incised channel at regular intervals along the channel to partially dam surface flow (Dobes et al. 2013). In so doing, the weir reduces the length of uninterrupted slopes and creates pools, interspersed by hydraulic jumps or run selections (Wiley 2017). The weirs also promote sedimentation, which in turn raises the stream bed height (Dobes et al. 2013). In places, these are also promoted to be combined with small floodplain structures to distribute water across the floodplain and drive floodplain alluvial recharge.

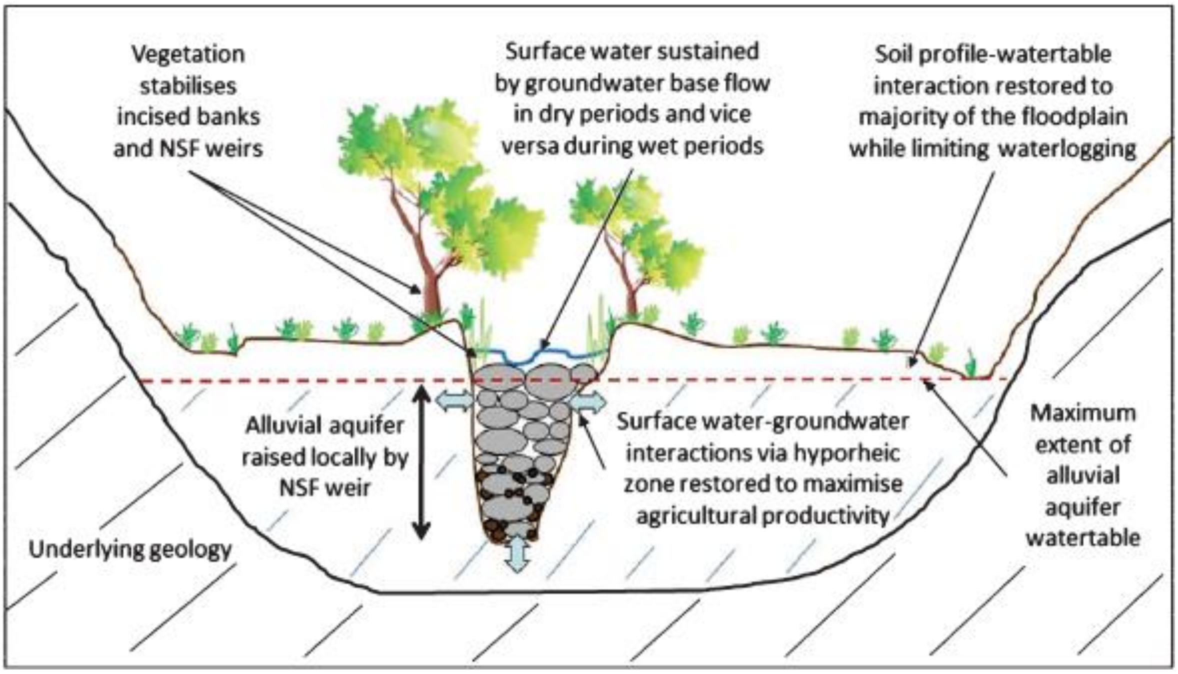


Figure 3: Grade control structure within an incised channel (Dobes et al., 2013).

Leaky weirs and the alluvial aquifer

A key aspect of grade control structures or leaky weirs is that it elevates stream level (DeBano and Schmidt 1989). This is central to the processes that NSF seeks to create, with Andrews describing at length as enabling recharge of the alluvial aquifer to occur and thereby raising the water table and retaining water in the landscape (Dobes et al. 2013). Andrews claims that recharge of the groundwater table results in the formation of a freshwater lens above the saline layer, effectively containing the saline groundwater (Andrews 2006). This has been attributed to the hydrostatic pressure that the freshwater exerts on the perched groundwater table (Newell and Reynolds 2005; Williams 2010), and the less-dense fresh water sitting over and displacing the more dense saline water and therefore freshening the surficial alluvial aquifer.

While there is data from well-studied unconfined and high transmissivity coastal aquifers that shows how freshwater lenses sit atop saline water, research focusing directly on the origins and presence of freshwater lenses that occur below rivers and complex alluvial aquifer systems is not widespread (Holt et al. 2019). There is a body of work that has identified groundwater systems, such as those of SWWA as being highly saline, despite the recharge with fresh rainwater. While there is some evidence for terrestrial freshwater lenses associated with gaining streams (Werner and Laattoe 2016), the large majority of literature documents their occurrence in a losing stream configuration (Cartwright et al. 2010). Freshwater lenses are beneficial in a range of contexts, including the provision of freshwater for irrigation and for sustaining low salinity baseflow of rivers during dry periods (Cartwright et al. 2010).

The majority of literature that focuses on density stratification of fresh and salty water within aquifers is described in relation to coastal systems, with high transmissivity and unconfined sand aquifers, and often in the presence of a mounded (inland) freshwater system flowing into or over a saline coastal layer. While Andrews and others within the NSF community refer to the density stratification of an aquifer as the same process as letting salty water stratify within a glass, the empirical evidence from an extensive body of hydrogeological research into salinity in dryland landscapes in SWWA shows no evidence of this occurring. Rather, the complex hydrogeological structure combined with the influences of salt movement under the processes of plant transpiration, capillary movement and exfiltration mean there is no evidence from decades of groundwater salinity research to suggest that the groundwater systems of SWWA undergo stratification similar to unconfined coastal aquifers or a glass of water. There is no evidence for stratified freshwater aquifers in SWWA, aside from localised hillslope sand-aquifer systems in a small number of landscapes.

Design criteria for control works

Implementing control structures to manage or manipulate water on hillslopes, but particularly within riverine environments, is work that typically involved the engagement of hydrologists, geomorphologists, water or hydraulic engineers. This is based on calculations relating to the materials (rocks, sand or trees and large woody debris) and their erosion susceptibility, the topographic potential of the setting considering factors such as valley and water surface slope and unit, and specific stream power settings. This forms the basis of the design of control structures based on risk to surrounding and downstream infrastructure and the environment. This would often be conducted in consultation with aquatic ecologists to consider aquatic populations within, upstream and downstream of control structures and impacts on aquatic connectivity.

Some NSF publications refer to the expense and associated barriers of these conventional approaches due to the costs of engaging professional design services. Within the NSF literature consulted as part of this review, there exists no published criteria or guidelines from which NSF practitioners or consultants should make such calculations. The specific basis and design principles of NSF and how earthworks for water management in relation to bank spacing or calculating permissible water velocities to reduce erosion is unclear. Furthermore, no guidance has been provided on impacts to catchment hydrology, surface water flows, and groundwater recharge arising from NSF interventions at the intervention location or on areas further downstream. No reference to consideration of aquatic connectivity and upstream, at-site and downstream impacts could be found from the body of available literature.

Summary

NSF has the aim to intervene in landscapes to rehydrate the landscape through increased water availability from a recharged alluvial aquifer, reducing channel incision and soil erosion, and addressing salinity. It seeks to:

- Reduce the velocity of surface flow through the landscape, increase surface water residence time, and redistribute flow across the floodplain.
- Emphasises the use of:
    - banks on hillslopes and at the hillslope-floodplain margins to spread water over the landscape
    - creation of secondary diversion channels
    - construction of grade control structures or leaky weirs
- Promotes the chain of ponds river morphology as the single optimal natural state of all rivers and landscapes with access to surface water runoff.

3.2. Revegetation of the Landscape

Maximising ground cover and vegetation succession in river systems is a key aspect of NSF in seeking to address issues of land degradation and promote biodiversity within the landscape (Dobes et al. 2013). It is known that riparian vegetation provides a range of services, including bank stabilisation, aggradation of sediment (Prosser et al. 1994), production of organic matter for soils (Hurditch 2015), moderation of water temperature by shading, buffering stream velocity (Zierholz et al. 2001), and providing habitat for birds and insects. On the hillslopes, vegetation plays a role in minimising the erosive capacity of runoff from hillslopes by retarding flow velocity (Norris and Andrews 2010). Thus, revegetation of the riparian zone and the hillslopes within the NSF framework is not a unique approach. Where NSF does depart from mainstream land management approaches is that it advocates the use of exotic plants and even declared weed species (including willows, blackberries and thistles) as a medium through which to revegetate the landscape.

NSF and weeds

Andrews (2006) advocates for using weeds as active agents of land rehabilitation. While this does not necessarily imply deliberately planting weeds, there is undoubtedly a focus on not seeking to control and suppress weeds as part of maximising vegetation cover and encouraging a plant succession process. Andrews (2006) states that the presence of weeds is an indicator of infertile soil and that if you let the weeds grow, the soil will recover. He discusses the recovery process as being enhanced by allowing weeds to grow and the pathway of colonisation and succession to include native species.

Andrews (2006) states that *"making biodiversity the basis of…agriculture"* is essential for farmers who wish to ameliorate costs associated with diseased animals and landscape management (p.94), and that biodiversity in the landscape is what enables the environment to *"cope with periods of stress"* (p.88). The NSF approach embraces weeds to promote biodiversity in the landscape because they are considered to contribute to the number of species in a given area and restore a balance between edible and inedible plants within the landscape. Andrews promotes weeds (typically inedible plants) as instrumental in contributing to soil health (by adding nutrients and minerals and increasing the carbon content of the soil) and thus providing a stable environment in which edible plants can recover from grazing pressures (p.90). Furthermore, because of their rapid growth cycles, Andrews (2006) claims that weeds are *"more effective than trees at controlling salinity…by a factor of 100"* (p.77) and that it is *"impossible to farm sustainably in Australia…without weeds"* (p.129). Andrews (2006) encourages farmers to allow weeds on their properties to flourish and grow and to only slash them after their growth cycle, after which they may be used as mulch (p.138). This then constitutes a form of "mulch farming" without the required input costs associated with mulch import.

NSF promotes a view of weeds in the landscape as an indicator of soil that lacks fertility. Weeds are viewed as colonisers that ultimately restore soil fertility and thus represent productivity in the landscape. Over time it is anticipated that native grasses and trees will then reclaim the landscape. This is highlighted as particularly important in the lower third of the landscape, where weeds serve as a filter and trap for sediment and nutrients, and by slashing, mulching and then adding back into the top third of the landscape, allows for nutrient cycling within a closed hillslope system.

There is very little published scientific or empirical evidence to support the views of Andrews in relation to weeds. The views of the NSF community are contrary to much of the published literature on weeds, which presents weeds in terms of the negative impacts they have on native vegetation or monoculture agriculture crops that require high herbicide costs to manage weeds in maximising profit from grazing and cropping agricultural systems. These negative impacts include competition with native species for natural resources (such as light and soil moisture, etc.) and effectively out-competing smaller plant species and emerging seedlings and thereby threatening flora and fauna diversity in the landscape (Robertson 2005).

There exists a range of conference and peer-review literature that identifies examples where willows have altered channel morphology and in-stream ecology, adverse water quality impacts through feedback mechanisms, also noting that willow removal has been a significant focus of land management and is a declared weed (Doody et al. 2011; Greenwood et al. 2004; Pope et al. 2007; Read and Barmuta 1999). In relation to water resources and willows specifically, Doody et al. (2011) discuss the beneficial roles that willow removal can have on increasing river flow due to lower evapotranspiration demand and evapotranspiration losses.

In relation to the use of exotic species in riverine areas to promote channel roughness and flows, Erskine et al. (2009a) found that *Casuarina cunninghamiana* Miq. was the most effective species in stabilising channels and that these species are both flood-tolerant and fast-growing and were shown to reduce water flow velocity while inducing sand deposition on the benches (Erskine et al. 2009a). Bush et al. (2010) directly highlighted the capability of natural species in stream rehabilitation and suggested these should be incorporated in the NSF model instead of exotic species.

NSF as part of a farming system

NSF calls for a fundamental shift in farming systems, dividing the landscape and production as follows (Andrews 2006):

- A third of the farm area should be for trees and scrub, focused on the hillslopes and crests,
- A third should be for cropping and active production (middle third), and
- The (bottom) one third allocated for grassland and weeds.

When revegetating hillslopes and crests, planting hedgerows that are at least 100 m wide is encouraged. Andrews (2006) does not suggest specific species but recommends that deciduous trees should be used because they generate significant tree litter, which creates mulch. Some of the NSF community hold species such as Eucalypts as highly unsuited to this system as they are fire-prone and evergreen so they do not produce the leaf mulching opportunities of species such as poplar or willows, which the NSF community promotes. For the lower grassland area, NSF promotes the spread of weeds, particularly thistles, which are claimed to have a high concentration of minerals and nutrients. Andrews (2006) claims that once the minerals and nutrients in the soil reach a “critical” level, native grasses will take over.

Andrews (2006) promotes the use of willows in the riparian zone for slowing water velocity and providing various ecosystem services (shading of water, bank stabilisation etc). NSF considers these pioneering species to be more time-efficient in rehabilitating the landscape as opposed to native species. NSF does not advocate for the revegetation of the landscape with native eucalypts, taking the view that gum trees make a limited contribution to soil fertility and do not facilitate the growth of smaller plants and grasses beneath their canopies.

Most primary producers in SWWA use farming systems that rely on large and efficient operations that require easy access of machinery to support grain production, with some engaged in mixed cropping and livestock production. Experts in farming systems, agronomy and primary production have questioned the compatibility and profitability of the NSF approach where only 1/3 of the landscape is used for cropping production and identify this as potentially incompatible with profitable farming systems through the grainbelt of SWWA. It is suggested that the approach of NSF as a profitable farming system is likely more suited to higher rainfall areas and high-value livestock production or operations that have primary production supported by off-farm income or other external financial support. This is highlighted by case studies where NSF has been used, where the majority are run with either a focus on high-value livestock production, run as equestrian operations and/or by people with off-farm income who are not necessarily engaged in full-time primary production as the only source of income.

Summary

Revegetation of the landscape with a biodiverse range of species is a central pillar of the NSF approach. To summarise:

- NSF presents a three-zone layout for a sustainable farming system in which a third is reforested, a third is used for cropping, and a third is a designated ‘recovery area’ comprised of grasses and weeds.
- NSF promotes revegetation with exotic species and declared weed species such as willows and blackberries and fostering weed cover across the landscape.
- Revegetation of the landscape with eucalypts is not encouraged as these are considered detrimental to the growth of smaller plants beneath their canopies.

3.3. Restore the Fertility of the Landscape

Another tenet of NSF is restoring fertility to the landscape. This is closely linked to the previous two components of NSF – namely, manipulating the hydrology and revegetating the landscape. There is no clear definition of 'fertility' within the NSF literature. However, within the NSF context, it appears that this term largely refers to the nutrients and minerals that contribute to soil health and thus to plant growth. Some of these nutrients and minerals include carbon, hydrogen and oxygen, nitrogen, phosphorous, potassium, calcium, magnesium and sulphur (macronutrients), as well as a number of micronutrients (Fertilizer Industry Federation of Australia 2006; Jones 2012). For the purposes of the discussion below, it's important to distinguish between 'fertility' as it is used in NSF and the term 'soil fertility', which, in addition to the soil's physiochemical properties (nutrients, minerals, and soil pH etc), also incorporates the physical properties of soil (such as texture, structure and water-holding capacity) (Jones 2012).

NSF and landscape soil fertility?

Soil organic matter, comprising decaying plant and animal matter incorporated into the soil, is one of the major sources of fertility in NSF (Andrews and Hodda 2008; Fertilizer Industry Federation of Australia 2006). Organic matter contains nitrogen, phosphorous, magnesium, calcium, sulphate and other micro-nutrients, which are essential for plant growth and which become accessible to plants as the organic matter decomposes (Fertilizer Industry Federation of Australia 2006).

One of the primary aims of NSF is to promote the accumulation of fertility (that is, the accumulation of nutrients in soils) and minimise loss of fertility from the landscape (Andrews 2006). The accumulation of fertility is linked to revegetation of the landscape (see Section 3.2), as trees contribute organic matter (and thus fertility) to the soil. This accumulation of fertility is concentrated on the hilltops and slopes (where targeted reforestation of the property occurs), with minerals and nutrients then transported downslope in above- and below-ground water to the cropping area (Norris and Andrews 2010). Soil nutrients that are subsequently leached from the cropping area are then intercepted by the weeds and other vegetation that populate the floodplain, thereby minimising fertility loss from the landscape (Andrews 2006). Minerals and nutrients are distributed across the floodplain via the secondary diversion channels (Section 3.1), with some of this fertility transported again to the top of the hills by insects, birds and grazing animals. These animals then also contribute to the generation and accumulation of fertility on the hillslopes.

NSF also promotes mulch farming as another method of accumulating fertility in the landscape. This method seeks to avoid damage to the soil caused by ploughing, instead using an undisturbed paddock with grass and weeds raked into windrows and crops planted between the parallel rows (Andrews 2006). Andrews (2006) considers this approach to be a commercially viable one for Australian farmers as it uses the slashed grass and weeds to add organic matter to the soil, simultaneously reducing the reliance on chemical fertilisers and herbicides (Young et al. 2002).

What does increased fertility mean for the landscape?

The sole purpose of increasing fertility within the landscape is to boost productivity. In theory, targeted reforestation will lead to increased soil organic matter and thus greater accessibility of essential plant nutrients to facilitate plant growth. However, soil rich in nutrients does not necessarily constitute a productive soil (herein defined as a soil that is able to support crop production), with other factors such as insect infestations, drought, and poor drainage potentially limiting production (Fertilizer Industry Federation of Australia 2006). Additionally, the physical properties of soil also determine the extent to which nutrients are accessible to plants – and optimising these physical properties of soil are not a core focus of NSF. Thus, while there is potential for increased production in an NSF managed landscape, this is dependent upon a range of other factors and not just dependent on the accumulation and retention of fertility in the landscape.

The review now considers evidence from NSF case studies (Chapter 4) and then summarises the ARC Linkage Final Report ("Restoring hydrological connectivity of surface and ground waters: Biogeochemical processes and environmental benefits for river landscapes") in Chapter 5 in rounding out the background to NSF.

4. Case Studies

4.1. Tarwyn Park, New South Wales

Setting

Natural Sequence Farming originated on Peter Andrews' upper Bylong Valley equestrian (later cattle) property, Tarwyn Park, in New South Wales (Andrews et al. 2005). The Bylong River intersects the property, which is characterised by an extensive floodplain comprising Quaternary alluvium, sands and gravels (to a depth of approximately 15 m) (Young et al. 2002) in a confined valley setting. The underlying geologic unit comprises the Singleton Coal Measures (shales, sandstones and coals), with the Permo-Triassic sandstones dominating the hillslopes (Young et al. 2002). The units are known to transmit groundwater, however, groundwater contribution to the floodplain is known to be relatively small. The Singleton Coal Measures are likely the most significant contributor of salts on the valley floor due to their high salt content (Young et al. 2002).

Before implementation of NSF on the property, Peter Andrews described the property as severely degraded, characterised by saline scalds, incised channels, and a pasture of low productivity (Newell and Reynolds 2005)

NSF Implementation

As applied on Tarwyn Park, NSF included the construction of divergent stream pathways across the floodplain and the installation of 'leaky weirs' within the stream channel. Additionally, contour banks were constructed on the hillslope-floodplain break to capture surface and sub-surface run-off.

Non-structural measures included avoiding surface irrigation, herbicide use, chemical fertilisers, ploughing on hillslopes, and dam water storage in areas where the Singleton Coal Measures were the dominant lithology (Young et al. 2002). Cultivation of the floodplain was also minimised and a planned grazing regime introduced.

Outcomes

A CSIRO expert panel considered the NSF methods applied to Tarwyn Park. They found an absence of any substantive empirical data to support a robust quantitative assessment that is necessary to thoroughly evaluate the approach's cost-effectiveness and viability, especially when seeking to apply similar methods in other landscapes (Young et al. 2002).

The expert panel concluded that the installation of the in-stream weirs effectively reduced stream velocities and promoted the formation of a river system that increased in-stream sedimentation (Young et al. 2002).

In terms of salinity, it was considered that the migration of salt from the property had been reduced by combining altered land management practices and manipulation of the hydrological regime (Young et al. 2002), but there were a number of factors quite specific to this region in relation to salinity.

The productivity of the floodplain had also increased and was attributed to the altered hydrologic regime whereby the pasture essentially self-irrigated, as well as due to improvements in soil structure and nutrient concentrations (in turn a consequence of revegetation of the landscape and grazing control) (Weber and Field 2010).

While the expert panel noted the positive outcomes of NSF as applied on Tarwyn Park, it highlighted that NSF's stated objectives to increase biodiversity and landscape ecology were not achieved (Young et al. 2002). There was no apparent evidence of vegetation succession occurring on-site and a distinct absence of native vegetation on the hillslopes. This had translated to low-species diversity and an inability to provide habitat for birds and other animals (Young et al. 2002). There was also the possibility that the implementation of NSF on Tarwyn Park could negatively impact properties downstream by altering sediment loads and from hydrologic manipulation.

Additionally, the panel highlighted the role of the underlying local groundwater flow system in NSF's effectiveness as applied at Tarwyn Park. Local groundwater flow systems are defined as systems where *“recharge and discharge areas are within a few kilometres of each other”* and which are *“dominated by fresh groundwater in porous floodplain sediments”* (Coram 1998). They concluded that NSF would not likely be effective in landscapes where an intermediate or regional groundwater system is dominant.

4.2. Baramul, Widden Valley, New South Wales

Setting

Baramul is a horse stud currently owned by Australian entrepreneur Gerry Harvey and is located in the Widden Valley, New South Wales (Rogers and Bauer 2006). It is intersected by Widden Brook, a southern catchment of the Goulbourn River, and is underlain by conglomerates, sandstones and siltstones of the Permo-Triassic Sydney Basin (Keene et al. 2007). The alluvial aquifer system is comprised of unconsolidated alluvial sediments, with the dominant soil type on the floodplain described as a sandy loam (Rogers and Bauer 2006).

NSF Implementation and Research Objectives

Leaky weirs had been installed at two locations on Baramul where Widden Brook intersected the property.

Rogers and Bauer (2006) undertook an investigation of these NSF sites to assess the effectiveness of leaky weirs and the NSF approach in relation to soil organic matter and nutrient uptake. Their investigation included an analysis of soil physical and chemical properties, nutrient concentrations, and electrical conductivity of water samples.

Outcomes

While recognising the scientific limitations of their study in terms of replicability, Rogers and Bauer (2006) report an increase in soil organic matter and soil moisture in the NSF floodplain sites as compared to the control sites. Soil nitrate concentrations were higher in the control site, while concentrations of exchangeable potassium were higher in the NSF site. Water samples measured for electrical conductivity (µS/cm), used as a measure of salinity, were lower at the NSF sites compared to the control sites.

An ARC Linkage Project (LP0455080) entitled “restoring hydrological connectivity of surface and ground waters: Biogeochemical processes and environmental benefits for river landscapes” was also established to evaluate the outcome of NSF techniques on Widden Brook. A detailed summary of the ARC Linkage report is provided in Chapter 5.

4.3. Home Farm (Mulloon Creek), New South Wales

Restoration works focused on Mulloon Creek, the main channel that intersects the Home Farm property owned by the late Tony and Toni Cooke. The property was bequeathed to the Mulloon Institute after their passing (Hickson 2017).

Setting

Home Farm is a property in New South Wales that is now managed by the Mulloon Institute (Hickson 2017). This region's climate is temperate to humid (Johnston and Brierley 2006), with mean annual rainfall of 600 mm (Hickson 2017). Home Farm is intersected by Mulloon Creek for six kilometres and constitutes one of the upstream 'floodplain pockets' along its length. Lower Mulloon is located downstream of Home Farm and is another of the Mulloon Creek 'floodplain pockets' (Hickson 2017). These floodplain pockets are underlain by alluvial sediments (Johnston and Brierley 2006), which accumulated over geological time due to extensive folding and faulting within the Lachlan Fold Belt. The Home Farm floodplain pocket is in a confined valley setting with the quaternary alluvium on the valley floor confined by the Lachlan Fold Belt's metasediments.

The regional groundwater system underlying the site comprises a sandstone aquifer, while lower Mulloon is a fractured and fissured granitic aquifer (Hickson 2017).

NSF Implementation

Works conducted on Home Farm included flattening and revegetation of the channel bank and installation of twenty-two leaky weirs within the channel in 2006. Revegetation within the riparian zone and changes to agricultural land management also occurred (Hickson 2017). Hickson (2017) also installed thirty-four piezometers to monitor groundwater levels at Home Farm and Lower Mulloon (the control).

Outcomes

Hickson (2017) attributed an elevated alluvial groundwater table at the Home Farm to the constructed weirs' effectiveness along the 2 km portion of Mulloon Creek that intersected the property. Ponds, reminiscent of the channel form promoted by Peter Andrews, had formed upstream of the weirs resulting in a stream level rise. Due to increased hydrostatic pressure, baseflow should have been reduced – although Hickson (2017) noted that there was still evidence of baseflow into the stream, more significant than what was recorded during an earlier monitoring round some years prior. The increased baseflow contribution had been attributed either to an incorrect stream level value in the 2017 monitoring round or increased contribution of regional groundwater from the underlying hard-rock aquifer (Hickson 2017).

Hickson notes that the presence of a "thick and porous vadose zone" at Home Farm was instrumental for facilitating additional water storage associated with a groundwater table rise. However, water table rise was minimal where impermeable clay units dominated the upper horizons.

Thus, while in some areas, groundwater levels increased on the Home Farm, in other areas, implementation of NSF was not effective due to impermeable soils in the upper horizons (Hickson, 2017). Additionally, Hickson (2017) reflects that the shallow alluvial deposits enable adequate and effective water storage compared to areas with thicker layers of alluvium, which are well-drained and would not be effective in inducing a water level rise (Hickson 2017). It was also noted that land management associated with NSF, including the inundation of floodplains during flooding events may exacerbate flooding local decrease streamflow availability for downstream properties during flows and low-flow periods (Smakhtin 2001).

4.4. Yanget, Chapman Valley, Western Australia

Setting

Yanget Farm is an 800 ha property located approximately 25 km east of Geraldton that has been historically used for cropping and grazing (O'Bree and Andrews 2017). The property spans multiple land systems, with part on Tertiary Sandplain over Jurassic Sediments (likely Yarragadee Formation) over Precambrian Northampton Block (Northampton Complex). To the northwest older material has been exposed and younger sediments stripped away to expose Precambrian material and includes skeletal *in-situ* weathered profile and some exposed crystalline basement, a land system locally described as the "sugarloaf" system. Mean annual rainfall for the area (station number: 8315) is 349.2 mm.

The owners of the farm, Rod and Bridie O'Bree engaged Peter Andrews to implement NSF methods on Yanget Farm in 2008, with most of the earthworks completed by the end of 2009. A key focus on the property is the production of cattle.

NSF Implementation

Specific NSF interventions worked with existing surface water management contours bank structures that pre-dated the O'Bree's purchase of the property. NSF interventions and modifications included construction of in-stream structures (leaky weirs) in areas identified by Peter Andrews as having 'natural steps in the flow line', and near-level contour banks with spill out points to spread water across the largest possible area (O'Bree and Andrews 2017). Manure is placed at the spill points so that nutrients could be spread across the landscape by water flow. Other interventions included reintroduction of perennial species to the landscape, specifically woody perennials higher in the landscape, water tolerant perennials on the floodplains, and perennial grasses and legumes (including green panic, Bambatsi panic, Signal grass, Consul Love grass, Siratro and Lucerne) in the mid slopes.

The growth of weeds on the property was also encouraged and were mechanically mulched (slashed) to facilitate the natural succession to higher-order plant communities. The focus was not necessarily on actively promoting the growth of weeds but rather on not trying to control them by spraying.

The landholder discusses the approach as exploiting them as ground cover and mowing and managing through controlled grazing to harness their ability to repair soils. This approach is credited with an increased cover over the landscape. The landholder sees the approach as creating a more resilient landscape, where erosion has been reduced, and soils are now developing. Their experience in more recent heavy rainfall events is that the landscape holds more water, there is less erosion and less surface runoff. The landholder credits the NSF interventions as managing salinity on the property. Some of these benefits may be property and prior-conditions specific, with the influences of past (over) grazing prior to O'Bree's purchase of the property, and relatively low stocking rates as potential contributors to surface cover and related benefits.

Outcomes

Outcomes highlighted by the landowner attributed to NSF methods applied on Yanget Farm include:

- Retention of water in the landscape after summer rainfall from leaky weir structures in creeks
- Persistence of perennial legume pastures under the current grazing regime.

4.5. Woods Property, Toodyay, Western Australia

Background

Located 6 km south west of Toodyay, Jack Woods' 377 ha farm is a recent example of a NSF intervention in Western Australia. Underlain by the gneisses, granites and migmatites of the Yilgarn Craton (Weaving 1999), the Toodyay regions receives a mean annual rainfall of 521 mm (Toodyay weather station: 010125).

A farm plan for the Woods property was based on the Yanget Farm model (Section 4.4), and developed by Tim Wiley and Rod O'Bree from Tierra Australia Pty Ltd. This was based on what they called a Catchment Function Analysis, with the aim of investigating the natural functions of the Harpers Creek catchment landscape and how these have been disrupted post-European settlement and how those natural functions could be restored to the landscape (Wiley and O'Bree 2020). The farm plan was developed for implementation over a period of three to four years.

The farm plan incorporated principles of landscape rehydration based on Peter Andrews' Natural Sequence Farming methodology, as well as elements of regenerative agriculture and carbon farming. The purpose of the farm plan was to obtain "environmental and agricultural outcomes" while also minimising vulnerability to wildfires (Wiley and O'Bree 2020).

NSF Implementation

Construction of leaky weirs in the creek line aimed to "restore a chain of ponds", as well as construction of new contour banks across the landscape are the major elements of NSF that were applied in the south-west corner of the Woods property on the creek catchment (Wiley and O'Bree 2020). The landscape was also divided according to land use zones (designating areas for native shrubbery, perennial pastures, native forest, pasture cropping) with revegetation efforts including both native vegetation and exotic tree crop species.

Departing from the NSF methodology, the farm plan also included aspects of holistic management whereby the landscape was divided into discrete grazing cells comprising enclosed paddocks to accommodate rotational grazing of stock. Each of the grazing cells (comprising up to eight enclosed paddocks) were centred around a central watering 'hub'.

Outcomes

Outcomes of the farm plan, particularly efforts toward rehydrating the landscape, are yet to be reported, though some interventions have started.

4.6. Outside Scope

Outside of the scope of this review are a series of NSF interventions in the Gascoyne, Murchison, Goldfields and Pilbara regions of Western Australia. The application of NSF principles to these systems, with their arid to semi-arid climate, sporadic to ephemeral flow regime, complex ecohydrology and groundwater interaction, means that these sites are not included in this review.

5. Summary of the ARC Linkage Project Report

This section presents a summary of the ARC Linkage Final Report (entitled "Restoring hydrological connectivity of surface and ground waters: Biogeochemical processes and environmental benefits for river landscapes") prepared by Southern Cross University in collaboration with the NSW Department of Environment, Climate Change and Water, Hunter-Central Rivers Catchment Management Authority, and G Harvey Nominees. The ARC Linkage Project was established to "*gather scientific evidence*" to assess the effects of NSF as applied at Baramul. This document represents the single most detailed scientific review of NSF intervention and its methods, success, and limitations.

5.1. Project Objectives

The ARC Linkage project sought to test the hypothesis that "*lateral and vertical hydrological connectivity is important for floodplain sustainability and can be improved by reinstating secondary floodplain channels and wetlands and creating artificial pools on the main stream*."

As such, the key research areas for this project focused on methods of stream rehabilitation, hydrology and hydraulics, channel and floodplain geomorphic processes, water quality and aquatic habitat, and fluxes in biogeochemical processes.

5.2. Project Setting

Setting

Baramul is a horse stud currently owned by Australian entrepreneur Gerry Harvey and is located in the Widden Valley, New South Wales. It is intersected by Widden Brook, a southern tributary of the Goulburn River in the Upper Hunter Valley, and is underlain by conglomerates, sandstones and siltstones of the Permo-Triassic Sydney Basin (Keene et al. 2007).

The study area itself comprises pastoral land in the riparian corridor of Widden Brook extending approximately 26 km upstream from Widden Brook's confluence with the Goulburn River, and with a catchment area of 708 km^2. Laterally, Widden Brook is confined by bedrock valley sides and river terraces.

The unconfined alluvial aquifer system (Somerville et al. 2009) underlying the study site is comprised of unconsolidated alluvial sediments deposited during the Holocene, with the dominant soil type on the floodplain described as a sandy loam (Erskine et al. 2009b). Deposition of alluvial sediments occurred throughout the Holocene, with major reworking of the floodplain and channel widening occurring since European settlement between 1831 and 1954/1963 (Erskine et al. 2009b). However, since the large flood event of 1955, there has been evidence of rapid channel contraction occurring within Widden Brook due to ongoing deposition (Cheetham et al. 2010) in the Widden catchment, and floodplain and bench accretion.

NSF Interventions

Application of NSF at Baramul involved manipulation of the hydrological regime in order to:

- Promote groundwater recharge of the alluvial floodplain,
- Reduce stream flow velocities and erosion,

- Raise the level of the sand-bed channel,
- Stabilise the stream bed and banks,
- Improve stream water quality, and
- Mitigate impacts of salinity on surface-ground by enhanced freshwater recharge.

Specifically, twelve bed control structures (leaky weirs) were installed along 6 km of Widden Brooke at Baramul between 2001-2010. The in-stream structures included rock-concrete structures, sand-rock / log barriers, and rock ramps. The report stated that the structures were not designed to accepted engineering specifications, and the crest at bed level and up to full bank height created a scour hole on the downstream side and a back water on the upstream side.

Secondary channels traversing the floodplain were constructed upstream of three of the in-stream structures to distribute surface water across the floodplain and recharge the alluvial groundwater table and facilitate the formation of freshwater wetlands. Revegetation of the riparian corridor with declared weed species (i.e. willows) was undertaken, and further facilitated through the construction of fencing to limit stock access.

5.3. Project outcomes

The major project outcomes can be summarised with respect to stream rehabilitation, channel and floodplain geomorphic processes, hydrology and hydraulics, and water quality and aquatic habitat.

Stream Rehabilitation

From the sedimentological records, Erskine et al. (2009b) show that Widden Brook is undergoing channel contraction (by bench formation) and has been doing so since the large flood event in 1955. They emphasise that historical in-stream structural controls in Widden Brook (post-1981, and including NSF interventions) have been particularly effective because they coincided with this period of natural channel contraction (Erskine et al. 2009b).

Within the study area, Erskine et al. (2009a) found that *Casuarina cunninghamiana* Miq. played an important part in accelerating bench development and subsequent channel contraction. These species are both flood tolerant and fast-growing and were shown to reduce water flow velocity while inducing sand deposition on the benches (Erskine et al. 2009a). Bush et al. (2010) thus highlight the capability of natural species in stream rehabilitation, and potential for these to be incorporated in the NSF model and that the promotion of exotic species was unnecessary.

Channel and Floodplain Geomorphic Processes

Keene et al. (2008) found that implementation of NSF rehabilitation stream works resulted in increased upstream sediment storage and a downstream bed-load deficit, thereby facilitating the re-formation of pool-riffle sequences in Widden Brook. Over the three years of monitoring, the research group found that pool depths in Widden Brook had increased, storing four times the volume of water than historically recorded. This creates greater geomorphic complexity to the channel as well as the provision of additional aquatic habitat.

Keene also noted the fortuitous coincidence of stream rehabilitation works coinciding with natural climate-driven changes in flood regime is also notable in regards to the accelerated rate at which the pool-riffle sequences developed (Keene et al. 2008).

Hydrology and Hydraulics

While Keene et al. (2007) identified strong hydrological linkages between surface water and alluvial groundwater table depths, they found only localised impacts to the hyporheic zone due to the in-stream NSF structural controls. Groundwater electrical conductivity values in the alluvial aquifer also generally increased with increasing distance from the in-stream structure, suggesting localised hydrological exchange between the stream water and groundwater near the in-stream structure itself.

Water Quality

Somerville et al. (2009) found that stream salt loads in Widden Brook have historically been highly variable due to variable baseflow in a dominantly recharging system. Leaching of saline groundwater into the surface water has resulted in increasing stream salinity downstream (Somerville et al. 2009).

Terrace groundwaters (intersecting sandy loam soils with clay lenses; EC: 800-2200 µS/cm) were generally more saline than alluvial floodplain groundwater (EC: 200-600 µS/cm) showing evidence of extensive mineral weathering (Somerville et al. 2009). Overall, Sommerville et al. (2009) concluded that mineral weathering was a "major contributor to salinity in catchments in the upper Hunter" – this in addition to mobilisation of salts in soils with a rising groundwater table as a result of vegetation clearance.

Summary

Overall, the ARC Linkage Report concluded that: *"Baramul NSF stream works have facilitated sand storage, vegetation recovery and localised channel-floodplain hydrological exchange, important for pool riffle development, channel contraction and hyporheic function."*

Bush et al. (2010) emphasise that NSF is not re-creating a chain of ponds river system but rather focuses on incorporating greater geomorphic complexity, and suggest that NSF methods are suitable for small upper catchment streams and gully systems *"dominated by local fresh ground water systems in highly transmissive floodplain sediments"*. Additionally, the efficacy of *C. Cunninghamiana* in promoting bench development and accelerating channel contraction essentially negates the use of exotic weed species advocated by NSF. The application of NSF at Baramul included limited stock grazing, and this was a vital factor in aiding revegetation efforts along the riparian corridor.

Risks associated with NSF interventions are particularly prevalent where channels or structures intersect river terraces, thereby promoting salt mobilisation in groundwaters with potential adverse effects to stream water.

6. Opportunities and Risks Associated with the Application of NSF in the south west dryland agricultural zone of Western Australia

Chapter 2 summarises the background NSF, while Chapter 3 summarises the types of interventions and objectives of NSF. The case studies presented in Chapter 4 present evidence supporting the application and challenges associated with NSF but also highlight the uncertainty of the NSF approach for managing degraded land, and provide limited detail on the application in the south west dryland agricultural zone of Western Australia. Chapter 5 summarises the most in-depth scientific review of Natural Sequence Farming but is based on work conducted on a single site in New South Wales.

This chapter begins by evaluating the specific interventions of NSF, in relation to the best available information for Western Australia (Chapter 6.1). Following this, a hydrozone approach is used to evaluate and summarise the impacts, opportunities, risks and efficacy of NSF interventions in the South West Agricultural Zone of Western Australia (Chapter 6.2).

Chapters 6.1 and 6.2 are developed from themes emerging from the literature review and guided from interviews with key knowledge-holders. This included: Natural Sequence Farming proponents and consultants; landholders who have implemented regenerative and NSF methods; hydrology and geomorphology consultants; and, experts in water, hydrology, hydrogeology, farming systems and regenerative agriculture. Interviews were conducted according to UWA Ethics Protocols and under Ethics Approval RA/4/20/6390, and consistent with this, individuals and organisations are not identified. Outcomes from interviews are organised into summarising themes.

6.1. Impacts, Opportunities and Risks of NSF Interventions in the South West Agricultural Zone of Western Australia

6.1.1. Landscape Rehydration

As noted in Chapter 3.1, NSF seeks to create a modified water-retention system in the landscape by constructing hillslope structures to retain water in the landscape, distributing surface flow across the landscape. Interventions also use in-stream grade control structures or leaky weirs within the active river channel to step-down water from one level to another, reduce water flow velocity, promote sediment aggradation and facilitate recharge of the alluvial aquifer.

NSF is promoted as an opportunity for landholders to improve land condition or reverse land degradation on their properties and increase production. The proposed benefits of rehydrating the landscape by reinstating an infrastructure that promotes water retention and capturing water from the hillslopes include greater water reliability, improved soil organic content and water savings (Hurditch 2015). This is expected to translate to increased productivity, an increase in productivity by as much as ten times, is suggested by NSF proponents.

From the interviews with NSF proponents, the single greatest principle of NSF is the belief that water is central to everything. Holding water in the landscape, as close to or at field capacity for as long as possible, is the single highest objective underpinning the approach of NSF and of the interventions, and central to the belief in NSF as a land management and agricultural production system.

Hillslope Banks

NSF contends that earthen banks constructed on the hills, floodplain, and at the hillslope-floodplain break prevent salts from reaching the floodplain aquifer, meaning that captured water is retained within the structure until it is lost by evaporation, flushed out by high floods, or leaks through the clay-lined interceptor bank. However, as discovered through the implementation of WISALTS banks (summarised in Chapter 2), the greatest risks associated with NSF arise from storing water in the valley floor and where hillslopes are seasonally at saturation and causing salinity, than come from landscape rehydration. Leakage of captured water through the clay-lined structure may serve as a source of recharge and has been found in WA to lead to secondary salinity, salt waterlogging and reduced production.

A key limitation of this approach for cropping systems in SWWA, has been the trends in broadacre farming to move away from engineering and earthmoving and even the removal of legacy surface water management infrastructure from the 60s, 70s and 80s to facilitate improved equipment movement, controlled traffic GPS farming, and with this increased efficiency and reduced soil compaction. People working in the agricultural surface water management areas have cited the transition to no-till farming as well as the drying climate as rendering much of this infrastructure redundant in the present day.

An additional issue that was highlighted, was the limited capacity and capability in industry to plan, design, supervise and build appropriate water management infrastructure which may present as a key issue for the implementation of NSF methods. Interviews with people familiar with conventional farming systems highlighted that while earthworks are expensive, the largest costs associated with constructing contour banks on the hillslopes were not necessarily the direct earthwork costs, but rather, the costs associated with lost production area. For many conventional operators, this would be a significant hurdle to the implementation of NSF, especially if other areas of the property are lost to production in accordance with the 1/3 approach proposed by Andrews (2006).

Practitioners of NSF methods who were consulted highlighted that structures were generally small, and in consultation with agencies, has been assured that both hillslope and in-channel structures were legal. They identified that structures were typically found in smaller catchments and upland areas, and the potential impact on downstream systems would be minimal in the event of a structural failure. They identified that the structures were generally built higher in the landscapes and in catchments with low salinity risk. Potentially relevant to NSF flow structures is the *Rights in Water and Irrigation Act 1914* (WA), section 17, that defines a dam as '*any artificial barrier or levee, whether temporary or permanent, which does or could impound divert or control water, silt, debris or liquid borne materials, together with its appurtenant works*'. The related explanatory note for the Act states that while private drinking water supply dams are outside of the scope, dams constructed for "*alternative or mixed-use purposes*" are within -scope (https://www.water.wa.gov.au/__data/assets/pdf_file/0008/4022/107820.pdf). As such, NSF structure may fit the definition of a dam under this Act. The note identifies the dam owner as responsible for dam safety and the need to engage suitable qualified experts with geotechnical and engineering knowledge to advise on technical aspects of dam construction. The explanatory note states that the dam must not cause harmful upstream or downstream effects, including impacting seasonal streamflow or causing the flooding of neighbouring properties, access ways or reserves. Where NSF structures are built in areas with surface water allocation plans, they may also require a water licence.

A key message from both NSF proponents and people delivering training in NSF methods and those working in the conventional agriculture sector and state agencies has been the reduction in skills and training in earthworks design and construction over the last few decades. Both groups highlighted that the State Agriculture agency has in the past trained many people in design methods for earthworks design, as well as earthmoving contractors, and there was a certain capacity within the system to support the types of work that NSF includes. NSF proponents highlighted that the interventions are typically small-scale hillslope water retention and spilling infrastructure and in-stream leaky weirs. They flagged cost as a significant barrier to engaging professional support, with almost no local capacity within Western Australia to support this type of work. This concern was reiterated by those from the consultant hydrology and geomorphology area, who also highlighted the cost of designing and engineering these structures as a major impediment to adoption as well as the limited training available for this type of work. The Certificate II in Conservation and Land Management through Geraldton's Central Regional TAFE was identified as one program that included site visits to the Yanget NSF demonstration property, but it is unclear whether this program included delivery of training in conservation earthworks as part of the curriculum.

No written guidelines or specific design information could be found for NSF interventions, and people who had attended training sessions stated that written design criteria were not provided. During the interviews, a range of opinions were share relating to the criteria and design process used for NSF earthworks. A common response was that the process involves coping the scale and size of NSF structures from workshops, and the adapt to local conditions. This typically involved building structure with available equipment and resources to replicate the structures seen in workshops and then refining the design when structures failed during moderate to large rainfall events. Some respondents commented that planning and design work was used to ensure that the size of structures was large enough to prevent any failure of overtopping.

Evaluating failures from building and experimenting with structures and then tweaking the design was highlighted as the key approach within the NSF community. There was a concern raised about earthworks design that isn’t supported by erosion and runoff calculations as well as poor earthworks construction techniques posing a risk of structure failure with potentially severe consequences for soil erosion and the potential to cause gully development and downstream sedimentation impacts. This applied to on-farm risks such as failed structures initiating gully formation, through to off-farm impacts on downstream areas. An interesting consensus was the need for better training and local (Western Australian) capacity to support this area. Most interviewees commented and agreed that poorly designed structures were a risk to both NSF proponents and to others.

Floodplain – Secondary Diversion Channels

On the floodplain, recharge of the alluvial aquifer is proposed to occur as water from the active river channel is ponded and then distributed across the landscape via a network of secondary diversion channels to rehydrate the floodplain.

Rehydration of the floodplain may pose a risk of waterlogging, particularly in the Wheatbelt (Zone of Ancient Rejuvenated Drainage) which are comprised of large quantities of clay. If applied on such a landscape, there is the risk of inducing waterlogging on the surface and thereby introducing another component of land degradation to the landscape (Pettit and Froend 1992). Rehydration of a landscape that is already at field capacity or waterlogged will negatively impact plant growth and thus will also have economic implications for productivity (Barrett-Lennard et al. 2005)(McFarlane et al. 1990).

Additionally, as with the construction of contour banks on the hillslopes, recharge across ancient river terraces with high salt content may also promote the formation of secondary salinity in these areas (Bush 2010). While bottom-up driven salinity is a known contributor of salinity in the landscape, Callow et al. (2020) show that surface water processes also contribute to the development of dryland salinity, particularly in the low-gradient landscapes of the Wheatbelt. Top-down inundation processes as conceptualised in the flow-fill-flood model can mobilise the vertical diffusion of salts resulting in surface expression of salinity, or contribute to downstream salt fluxes (Callow et al. 2020). Interviewees stressed that salinity as defined in the areas where NSF originates (the Upper Hunter) is not directly comparable to salinity in the WA grainbelt, in processes, extent and severity which are much more severe in SWWA. This is particularly relevant when considering the mechanisms that drive salinity in these settings, as well as the way in which saline land is defined as an order of magnitude. Experts working in the surface water and hydrogeology salinity areas for many decades identified many examples of salinity development in any locations where water is held up and where ponding occurred. This included locations of WISALTS banks and where people have followed approaches to pond and retain water, including on hillslopes.

Fresh Water Lens Formation

As noted in Section 3.1, very little published data information exists to support the mechanisms that drive the formation of freshwater lenses in inland settings that Andrews describes in his publications. NSF proponents who were consulted simply pointed to the experience of Andrews and the experiment of putting salt into water and that water stratified into denser salty water and fresher less-dense water. All hydrogeologists consulted universally agreed that while this mechanism exists in a glass and occurs in high transmissivity coastal systems, there is no evidence for this occurring in aquifers across the WA wheatbelt. They pointed to over a century of evidence of significantly larger volumes of fresh rainfall recharging the aquifers of the Wheatbelt since land clearing. They concluded that if this mechanism (NSF promoting aquifer density stratification) had any merit, there would be tens of meters of freshwater overlaying saline water across the Wheatbelt and this would be widely exploited. Hydrogeology and groundwater experts identified this density stratification phenomenon as occurring only in high porosity and transmissivity settings such as sand islands, but that all evidence suggests that Wheatbelt valleys experience a vertical exchange of fresh and saltwater movement under the influence of vegetation, surface ponding, exfiltration and diffusion. There is simply no conceptual or empirical evidence to support the aquifers of the WA Wheatbelt as conforming to the density stratification mechanisms described by Andrews and NSF proponents. In valley-floor systems and most hillslope soil types (aside from localised, perched seasonal sandplain aquifers), all available evidence suggests that any mechanisms that promotes enhanced groundwater recharge will exacerbate salinity in the WA Wheatbelt.

River Channel - Grade Control Structures / ‘Leaky Weirs’

Interventions within the active river channel should broadly be considered regarding the intended geomorphic alteration to the river channel. NSF describes this as simulating a ‘chain of ponds’ river system and the likelihood of desired results, such as forming a freshwater lens in the alluvial aquifer.

Chain of Ponds – Is this viable in a West Australian context?

The work of NSF seeks to simulate a chain of ponds river system within the landscape (Andrews et al. 2005). While this might be feasible in selected locations of the eastern states where chain of ponds has been observed and historically documented, and still occur in some natural settings, this is not the case in Western Australia. Rivers in Western Australia are typically low-grade multi-channel systems which are not consistent with the stepped landform chain of ponds river geomorphology. Additionally, most regions in WA do not have sufficient rainfall to produce the peaty sediments characteristic of chain of ponds environments. Thus, attempting to introduce a chain of ponds river geomorphology in WA would simply not be in accordance with either remediation or restoration of the natural system. This then would be in direct opposition to the stated objectives of NSF to harness previous landscape functions to *"introduce systems that simulate the systems in the landscape long ago"* (Andrews 2006: p.187). As outlined earlier, expert reports found that the types of interventions do not create a chain of pond river morphology, even within the landscapes of New South Wales.

In discussing this point with NSF practitioners, the suggestion was made that Andrews sees this as the single optimal state for all systems. It is not that "chain-of-ponds" is endemic to a particular landscape and needs to be re-created, but the view that this is the single optimal state that is the template for everywhere. It is the "chain-of-ponds" morphology that represents the stepped-diffusion systems of broadacre hydroponics that the NSF community holds as central to these principles of land management. This is a very different approach to the geomorphology community comments where land management is approached from the basis of understanding what is natural.

Leaky Weir Construction

Earthworks associated with the construction of in-stream grade control structures were evaluated by the ARC project, in relation to NSF intervention works at Tarwyn Park. They concluded that structures were not built to accepted engineering specifications and standards. Experts consulted stated that they have never seen evidence of the basic design calculations for how the principles and design of earthworks for water management in relation to bank spacing or calculating permissible water velocities to reduce erosion has been applied to the case studies or other locations. A common theme was the lack of detail and published criteria on hydraulic design and no training manual provided within training sessions that detailed information on making calculations as part of training and field demonstration sessions. It was identified that the earthmoving and soil conservation community in SWWA have become less skilled over the last few decades as previous extension and training services around the design of surface flow structures, calculation and design training that was previously undertaken has been discontinued. Multiple interview respondents highlighted the limited design detail from promoters of NSF and the shortage of skills in planning, designing, and building the required structures, as key issues in implementation of NSF. Frequent responses from those involved in NSF interventions was that they started with the basic recommendations or approaches from attending training programs or in some cases, the direct recommendations of Peter Andrews, and then learned from doing. When structures failed, they learned and adapted to experiment and find what worked and what did not work.

Impacts to Downstream Properties

NSF practices also promote sediment aggradation up-stream of the grade control structures. While this has the benefit of filtering water flow and repairing areas where deep incisions may have occurred, Wohl et al. (2015a) caution that changes to the sediment load can result in loss of biodiversity, habitat, or ecosystem services within the riparian zone. Sequestering sediment load and nutrients upstream may also have negative flow-on effects in terms of productivity and streamflow for properties downstream of the NSF restoration site (Young et al. 2002). Thus, changes to the river structure and the processes that govern that system need to be considered on an individual property basis (Wohl et al. 2015a).

Extraneous materials introduced in the active river channel for the construction of the leaky weir structures are unlikely to pose a risk to downstream properties. Rock dump leaky weirs, for example, are minimal features with no significant risks from failure due to their smaller size. However, as noted by one of the interview knowledge-holders, instances where larger materials have been uses (such as logs) and in situations where the river has flooded, these materials can be damaging to downstream properties.

Other considerations of NSF Interventions in WA

Inappropriate and inadequate design of control structures was highlighted as an issue in the ARC report on works at Baramul. An issue raised during the interviews was the lack of clear design criteria specified for these structures and then the potential that failures could pose risks to the property owner and downstream. An additional factor that was identified is the point at which implementing these structures, starting with hillslopes and then into rivers, triggers considerations under the *Rights in Water and Irrigation Act 1914* or other legislation that relates to implementing control structures that impact on catchment hydrology. Within *Rights in Water and Irrigation Act 1914*, section 17, defines a dam as 'any artificial barrier or levee, whether temporary or permanent, which does or could impound divert or control water, silt, debris or liquid borne materials, together with its appurtenant works'. A concern raised in interviews is that these structures are explicitly designed with the desired impact fitting the definition of a dam and are not being planned or approved in a manner consistent with this or other legislation. Equally, during interviews, people identified that during the discussion with responsible state agencies, no issues had been raised in relation to structures applied as part of NSF interventions.

6.1.2. Landscape Revegetation

Revegetation of the landscape poses several potential benefits including stream bed and bank stabilisation and provision of habitat in the riparian zone, and reduction of flow velocities and erosion on hillslopes. Additionally, vegetation is a source of organic matter and nutrients for the development of nutrient-rich soil profiles. Revegetation of the landscape may also work to sufficiently de-couple the capillary fringe from the surface and break the cycle of inundation and exfiltration of salts in the soil profile. Mulching, which is heavily promoted by NSF, has been associated with benefits of evaporation suppression and reducing salinity risks.

People from the conventional agricultural sectors suggested that while the construction of physical structures to retain water in the landscape are likely unhelpful (and may actually prove counter-productive), the promotion of reduced grazing pressure by NSF, especially if associated with the (re)introduction of salt tolerant species, such as the salt lake mallee, swamp paperbark and grey buloke (Department of Primary Industries and Regional Development 2020), could benefit saline landscapes. Furthermore, increasing vegetation cover in the landscape may present carbon farming opportunities with the ability for increased carbon storage in these areas.

A point raised during interviews in relation to NSF and soil fertility was that demonstration case sites showcasing low-input systems are potentially accessing a storage bank of legacy nutrients in the soils. The availability of phosphorous in these systems was identified as a key factor, with current levels of productivity potentially linked to legacy phosphorus. Thus, in many of these low-input and low-cost operations, production and profit forecasting needs to consider the depletion of the soil nutrient bank, especially where key elements such as phosphorus are not being replenished. The suggestion here is that any data on returns from grazing as based on run-down of legacy nutrients and not a measure of the direct efficacy of a low-input farming system.

The conventional agricultural sector agreed that any methods that control grazing pressure and maximise vegetation cover are to be strongly advocated for. Conventional good grazing practice such as monitoring grazing pressure or techniques such as rotational cell grazing or the practices associated with NSF that lead to better ground cover are all beneficial. In relation to wind erosion, any method promoting enhanced vegetation cover is beneficial for the landscape. The presence of more trees and shelter in the landscape is beneficial to livestock systems and known to improve offspring survival. This viewpoint is consistent with the ARC summary report that found the greatest benefits from NSF were associated with transitions to a lower grazing pressure that allowed a better vegetation cover which protected the soil from erosion.

NSF emphasises the use of fast-growing, exotic species including willow (*Salicaceae)*, a number of which are listed as Declared Pests within the Western Australian Organism List (WAOL). The Western Australian Department of Primary Industries and Regional Development (DPIRD) regulates harmful plants and declared weeds under the Biosecurity and Agriculture Management Act 2007, and interventions to promote the use of exotic species as part of NSF should be made with reference to WAOL (https://www.agric.wa.gov.au/organisms). However, in the saline, non-productive areas, weeds may prove highly beneficial in managing evapotranspiration through vegetation and through mulching to suppress surface evaporation (Pettit and Froend 1992). The suppression of salt-concentration processes at the soil surface will drive the opportunity for greater leaching and lowering salt concentrations (Pettit and Froend 1992). In non-saline areas, it is suggested that revegetation works include the use of native species like the river oak (*Casuarina cunninghamiana*) which have been shown to be equally effective as willows at providing similar services (Bush 2010). Interviewees identified the role of *Allocasuarina* and *Melaleuca* species in colonising disturbed areas within river systems of SWWA. Thus, where NSF revegetation efforts are not accompanied by the construction of water retention structures, this regenerative practice may prove beneficial in SWWA.

The NSF practitioner community reported a variable approach to the use of vegetation and use of weeds. Some highlighted that they adapt the advocated policies and tend to not use willows or blackberry (which Andrews strongly advocates for the use of, or at least encourages to not suppress), and prefer to use species such as *Casuarina* and *Melaleuca*. Many NSF proponents did suggest that Eucalypts are poorly suited to the Australian landscape – being highly fire-prone and producing limited leaf mulch of limited nutrient value. These people tended to strongly advocate for the use of deciduous trees, and species such as willow and poplar, which they considered better suited to the optimal natural state for Australian ecosystems (despite being non-native species) according to the ideas of Peter Andrews. These trees serve an important role in providing leaf litter and mulch, and NSF proponents note an association of these species with fire suppression.

Modelling conducted in Western Australia (George and Bennett 2004) identified that achieving salinity benefits through revegetation programs will vary according to the landscape and underlying groundwater system. Local groundwater systems with a moderate slope (greater than 4%) were predicted to be more efficient in achieving salinity benefits through revegetation. While Andrews advocates for 1/3 of the landscape to be converted into trees and 1/3 to be weedy grasslands, even landscape revegetation at this scale is unlikely to reverse the impacts that land clearing for agriculture has had on the altered hydrological balance and secondary dryland salinity, with a suggested 80% landscape revegetation required to return hydrological balance (Hatton and Nulsen 1999).

A key theme that emerged from interviews was questioning the financial viability of the 1/3s approach of NSF advocated by Andrews. Revegetation of the hillslopes and reduced cultivation of the floodplain could also negatively impact farm profitability, primarily if the area to be used for cropping is limited to a third of the property, as advised by Peter Andrews. Several interviewees working in the farming systems area questioned Andrews' claim of a five to ten-fold increase in yield/productivity under the 1/3s approach. Farming systems specialists concluded that the claims of a productivity increase from NSF and potential losses from a reduced cropping area, were not credible or plausible given soil fertility and rainfall regime constraints in SWWA. When pressed on this issue and the feasibility of a productivity increase under NSF, most NSF proponents highlighted this productivity potential as being associated with the ways that NSF interventions can retain soils in a state of water availability at or near field capacity.

NSF proponents made the point that while NSF may not measure up financially for broadacre grains farming, they argued that in conducting an economic assessment of NSF against conventional farming systems, it is essential to consider the purpose and underlying principles of NSF. They identified that NSF seeks to address the harm that conventional farming systems cause – high chemical usage that impacts the farm and off-site environment, and the run-down of soil health amongst other issues. They argued that the full costs of any farming system needed to evaluate the full extent of operations, namely that in addition to considering the economics of input and output related to on-farm operations, the off-farm impacts and externalities such as the harm to the environment that they claim to be associated with conventional farming systems should also be taken into account.

Several interviewees noted the association of NSF case studies with particular types of farming operations: high-value equestrian stud; and operations with significant off-farm income or other financial subsidy supporting the primary production. Typically, NSF case study properties were cited as running a low number of high-value livestock, with some seeking to take advantage of the NSF (or other) status to derive a market premium for production. NSF as a profitable farming system was commented as being most applicable to the higher rainfall, non-broadacre cropping areas of SWWA. Areas proximal to larger regional centres and the Perth CBD which provide additional commuting options for people to derive an off-farm income whilst enjoying a farming lifestyle that incorporates NSF principles, or areas with higher rainfall and productive soils to support high-value livestock operations and with market proximity were identified as locations where NSF may be more commonly applied.

Posed with questions related to the viability of the NSF farming system and reliance on enhanced productivity from a smaller area of the land, a common response was to, in turn, question the viability of the conventional farming system and the lack of accounting for externalities and impacts of those systems on the broader environment. NSF proponents conceded that the economics may not be sound but highlighted that conventional farming systems do not consider the costs of land degradation and off-site impacts. They highlighted that conventional farming systems degrade soil structure and soil carbon, lead to excess leaching of water to the groundwater table which has been associated with much of the landscape turning saline, and facilitate the export of pesticides and chemicals with impacts to neighbouring properties and other industries (such as aquatic ecosystems and fisheries). NSF proponents claim that conventional agricultural systems are highly profitable because the external impacts are not costed into these systems. They concluded that any direct comparison and evaluation of NSF, therefore, required a holistic assessment of net profit and net impact. It was beyond the scope of this report to undertake such an analysis.

Most people in the agricultural sector consider NSF to be a non-economically viable option for a profitable broadacre agriculture operation, particularly cropping. This is particularly true of farmers in vulnerable landscapes characterised by lower gradients and rainfall. Farmers in these landscapes are required to work as efficiently as possible to produce a profit, and the inability to efficiently navigate machinery around paddocks, and the subsequent impacts on production, mean that NSF simply would not be an attractive or viable alternative for these farmers. NSF was identified as most suitable to areas that favour generation of an off-farm income to support a farming lifestyle that incorporates NSF principles, or higher rainfall areas with productive soils to support high-value equestrian or livestock operations with market proximity.

6.1.3. Summary of the Benefits, Opportunities and Limitations from NSF

A common theme across all respondents in relation to vegetation cover and NSF is that any system that encourages higher retention of vegetation cover is likely to be beneficial for soil and wind erosion. The ARC report highlighted this, citing that the reduction of livestock numbers and lower grazing pressure was the greatest influence on vegetation cover. There was some variability in responses from NSF advocates in relation to the use of weeds, including species such as willows, blackberry, thistle, poplar and other exotics. Some strongly supported the view that these are the optimal plants to create the ecological succession processes as proposed by Peter Andrews, whereas others stated that they thought other plants that are either native species or of known higher nutritive value as pasture should be used in preference to those suggested by Andrews. There was minimal empirical evidence of the success of either the weeds-focused or more native equivalent approach, other than the work from the ARC-evaluation work suggesting Casuarina was as effective, if not more effective, than willow in riparian areas. There was commentary suggesting that pasture quality on NSF properties was of generally low quality and nutritive value from observations, but there is no hard evidence of this, or direct evaluation studies. Some people interviewed highlighted the logical steps, that if NSF in either encouraging or not actively managing weeds, this is likely to lead to weeds and plants of low nutritive value and sub-optimal pasture quality relative to make actively managed pastures.

A common theme that emerged from the interviews in relation to earthworks was a consensus from the agriculture, consultant hydrology/geomorphology and NSF communities that there is a serious deficiency in design skills, capacity, and knowledge. People in the NSF community recognised the risk that untrained people undertaking the construction of structures posed to the “licence to operate” if these were to fail and cause downstream damage. All cited the deficiency in expertise and training by State agencies in recent decades and the barrier of cost in seeking engineering firms to undertake the design of these relatively small-scale structures. All highlighted a need for intermediate expertise – people trained and skilled in earthworks design and calculations, but not necessarily trained and certified hydrological engineers. Some interview participants suggested that expertise such as geomorphology or hydrology consultants, together with aquatic ecologists, are critical in designing in-stream structures and work in any first-order and larger stream or river should be left to trained professionals due to the potential for impacts on downstream properties and the environment. Some consultant geomorphology/hydrology people highlighted that there are high costs in their services due to the professional indemnity cover and extensive training as certified flood/hydrological/hydraulic engineers or certified consultant geomorphologists. The interviews did not establish whether NSF practitioners held professional indemnity cover for in-stream work and where the liability for downstream impacts lies (the landowner or NSF practitioner).

A key area where the views strongly diverged was in relation to the impacts of retaining and ponding water in the landscapes of SWWA and the likelihood of areas turning saline. The NSF community held to the views of Andrews, supporting the concept of density stratification of fresh above saline water within aquifers and preferential aquifer recharge will benefit all areas, including those with saline water tables. On this matter, there is a strong body of evidence from NSW and from WA, that ponding water in a landscape that is underlain by a saline water table, leads to areas becoming saline. All consulted hydrogeologists stated that there is just no credible evidence for this mechanism to operate within the aquifers of SWWA, and decades of groundwater (and surface water) salinity research has never reported evidence for this mechanism. They also identified very stark differences in the nature of the groundwater systems and store of landscape salt, rainfall, evaporation potential as well as geomorphology and seepage/recharge mechanisms.

Interviewees working in the salinity and farming systems area identified that individual landowners have the choice as to how they choose to manage their own land. Individual landowners should assess the risks that may arise in adopting NSF methods on their property. Landholders should consider the context of their property in relation to landscape, rainfall, soils, and susceptibility to salinity, as well as a host of potential issues that may arise including:

- The limitations in climate (rainfall relative to evapotranspiration potential) and the lack of sufficient rainfall and fresh water to rehydrate the landscape to the point that soils are maintained at field capacity.
- Direct evaporation accounts for significant losses of ponded surface water, which is therefore not transpired and used for vegetative growth (crops or pasture).
- Capillarity mechanisms that drive the movement of salts from saline groundwater to the surface, allowing the vertical exchange of salt from watertables and the unsaturated zone to the soil surface, causing salinity and salt scalding.
- Salt-waterlogging is a major production limitation in SWWA.
- Evidence from decades of field investigations, reports and peer-review publications concludes that drying and breaking the surface and groundwater link is key to addressing salinity. Mounding and leaching are effective management solutions. Almost all locations where landscape wetting and surface water ponding occurs is associated with the development of salinity and low productivity soils.

Beyond the individual property, there is likely to be minimal or no adverse off-site impacts from the methods using NSF methods, aside from where:

- The failure of larger in-stream structures or hillslope structures lead to significant gullying, erosion or sedimentation.

- Flow retention structures causes secondary salinity and downstream export of excess salts or where these structures adjoin neighbouring properties and cause salinity.

The chief conclusions reached by these experts working in the salinity and farming systems area is that the full adoption of NSF principles will not likely represent a profitable primary production enterprise for the majority of operations in SWWA. They suggested that NSF is likely to be more suitable for people who are not seeking to maximise profit from the farming enterprise. They stated that it is not the purpose of government agencies, the natural resources sector, agronomists, consultants or others to impede decisions in relation to how landholders choose to manage their own land, but it also should not be the role of these groups to invest resources to prove or validate any particular farming system. There is, however, a need and obligation to base advice on the best available science and empirical evidence. This group concluded that at present, there no compelling support that the ideas of NSF presents a new farming paradigm for SWWA.

Understanding the "naturalness" part of NSF

The term "natural" is somewhat confusing in this context in relation to NSF. NSF proponents maintained that NSF is less about restoring what is natural or pre-disturbance to an area, and more about creating the singular or optimal "natural sequence" or order that applies universally to the Australian landscape. This is focused on what has been termed the "natural sequence" or alternatively what some within the NSF community preferentially refer to as "stepped diffusion broadacre hydroponics". The focus of NSF is about a single motivation to (re)create a system that slowly steps water through the landscape. When challenged on the question of how NSF principles are adapted to different landscapes with different soils and climate, the response was that the single most important thing in NSF is water and ensuring soils are held at field capacity. At this point, everything else – including soil types and climate – becomes irrelevant. This is a key insight into how some NSF proponents view the objectives of NSF and its application to landscapes across Australia. NSF does not represent a philosophy and approach to land management that is related to what is endemic, native or "natural" within a specific landscape. Rather NSF can be thought of as bringing in a single view or perspective related to the optimal state for the Australian (or any) landscape, which is that the natural state is that all landscapes should function as a system of stepped diffusion broadacre hydroponics.

Suitability of NSF to landscapes within SWWA

From interviews, several locations that both the NSF proponents and experts in hydrology and hydrogeology suggested as more suitable within SWWA emerged, and this was restricted to:

- The rejuvenated and steeply sloped catchments near the Darling Scarp of the Avon Basin (e.g. Toodyay, Northam, York areas)
- Areas of the Chapman Valley (Sugarloaf System)
- The higher rainfall and hydrologically connected catchments draining to the coast from Perth to Esperance (the south west and south coastal areas of WA)
- Limited areas of sandplain systems in the Swan Coastal Plain and Perth Basin with no salinity risk
- Applied with caution in sandplain systems in the medium rainfall zone with no present surface salinity issues (e.g. Meckering & Wongan Hills area), and on skeletal soils in

rejuvenated systems where rainfall is above around 350 mm areas, and some similar land systems along the south coast

These areas can be summarised as those that are well-drained and contain very localised or fresh groundwater systems that have a low risk from secondary salinity.

Widespread adoption of NSF principles across the broadacre cropping and mixed grazing-cropping farming systems of the grainbelt of SWWA, was considered highly unlikely for reasons outlined below:

- Using only ⅓ of the land for cropping is not a profitable farming system, with experts in farming systems considering purported productivity increases as not realistic within the soils and climate of SWWA grainbelt.
- Due to no-till and the drying climate, there are not the surface water issues that farmers needed to address in the 70s, 80s and 90s. Many growers in broadacre systems are removing surface water management structures to allow easier access with machinery. It was identified that one of the greatest costs when conservation earthworks were evaluated was loss of productive land, compounded by impacts on the efficient movement of farm machinery.
- Grain farming systems and profitability are maximised where crops convert the maximum volume of rainfall into growth and water is available to the crop at relatively homogeneous rates across paddocks that grows a consistent crop. NSF emphasises concentrating water in certain areas of the landscape and the use of rainfall for enhancing groundwater recharge.
- Available evidence from the construction of flow retention structures across the grainbelt is that these are associated with land degradation by waterlogging and salinity.

Members of the NSF advocate community did not necessarily disagree with this summary but pointed out that NSF production systems are bearing the cost of dealing with many of the externalities that these systems do not contend with. This includes the impacts and costs from rising water tables and lost saline land, off-site chemical impacts and other externalities that are not factored into the economic evaluation of cropping and mixed-livestock systems.

6.2. A Hydrozone approach to potential risk and opportunity of NSF in the South West Agricultural Zone of Western Australia

A key finding of the expert panel review conducted by CSIRO, was to consider NSF in the context of the unique factors of each landscape, such as climate, geology, hydrogeology, and soils (Hobbs and McIntyre 2005). A summary of constraints that limit the implementation of NSF in various landscape settings (Young et al. 2002) is presented in Table 2, below.

Table 2: Landscape features that govern the applicability of NSF in various landscapes

Landscape Feature	NSF Application
Climate	The majority of case studies relevant to regions with >450 mm rainfall in Eastern Australia
Geology	Underlying geologic unit should have low contribution to the floodplain environment. Alluvial aquifer bounded by bedrock to limit deep drainage and maintain high water table
Landform	Confined valley setting Historically a chain of ponds river system (i.e. not incised channel)
Floodplain sediments	Coarse sands and gravel with high transmissivity Sediments sufficiently deep to allow water storage Salinity of groundwater in floodplain sediments must be low
Groundwater system	A local groundwater system must be present (these generally occur in areas of high relief such as foothills to ranges
Depth to groundwater	Shallow – otherwise recharge of the alluvial aquifer will be insignificant in terms of rehydrating the floodplain

Overview of South-West Agricultural Region

This section considers the potential for implementation of NSF across different landscapes of hydrological zones in SWWA. The south west agricultural region of Western Australia is an area of approximately 25 million hectares (ha) of which 16 million ha are used for agriculture (Raper et al. 2014). The region is characterised by a temperate to arid climate (Peel et al. 2007) and is tectonically stable, with a relatively flat topography and deep weathering profiles (McFarlane et al. 2020).

Due to extensive land clearance in large portions of the south west, and the transition to farming with shallow-rooted annual crops, dryland salinity has become increasingly prevalent across the region with rising groundwater tables and mobilisation of soluble salts (Raper et al. 2014). In the south west, approximately one million ha was considered to be salt-affected in 2004, with the majority of land posing a salinity hazard located on cleared agricultural land (McFarlane et al. 2004).

However, recent research published by McFarlane et al. (2020) suggests that land degradation issues associated with salinisation and waterlogging may decrease in some areas as a result of the drying and warming climate that has dominated the south-west over the past four decades. While this is positive in terms of managing saline soils, it implies reduced water availability.

Characterisation of hydrozones and NSF applicability

To consider the application of NSF in SWWA, this section will first categorise and characterise hydrozones, based on similar hydrogeological, climate, landscape and farming applications (Raper et al. 2014) in the south west according to their geology, soil types, hydrogeology, landform, and extent of salinity. Hydrozones have been grouped according to the broad hydrozone categories presented in McFarlane et al. (2020), however, within these broad groups, the more detailed hydrozones presented in Raper et al. (2014) have been applied. These hydrozones have been summarised in Table 3, with an additional column included to evaluate whether NSF would be suitable in that area relative to the criteria for effective NSF implementation presented in Table 2.

Risks and opportunities by hydrozone

The likely risks to the landscape resulting from the implementation of NSF methods are summarised in Tables 4-10. This considers the risks in relation to wind and water erosion, soil acidity, soil organic carbon, soil compaction, water repellence and dryland salinity, and are assessed for each hydrozone. In some instances, the methods promoted by NSF, particularly as it relates to large-scale revegetation of the landscape, present a negligible risk to the landscape, with the potential to ameliorate an existing land degradation issue. In other instances, and this is particularly true of where rehydration of the landscape is in view, risks to the landscape are considerably greater.

Table 3: Hydrozone characteristics and NSF applicability

Hydrozone		Geology	Hydrogeology	Soils	Landform	Climate [2]	NSF Applicable
Wheatbelt: Zone of Ancient Drainage (Largely Cleared)	Northern Zone of Ancient Drainage	Underlain by Archean granitoids of the Yilgarn Craton	Local groundwater systems hosted in gritty clay saprolite (to 30 m depth, formed from in situ weathering of basement rock). Yields are low; majority of groundwater (particularly in valley floors) is saline. Perched aquifers in deep sands on hillslopes contain fresh groundwater (small supplies)	Loamy to clay soils (valley floors); coarser textured loamy to sandy soils (upland areas).	Subdued relief, broad valley floors. Cleared for agriculture: 82%	~250-300 mm	Unlikely. The clay soils would hinder infiltration of water on the floodplain. Additionally, soils are likely to contain high salt levels (direct weathering product) and likely to exacerbate salinity.
	Southern Cross	Underlain by the mafics and metasediments of the Southern Cross Greenstone	Groundwater at 10 to 40 m in the greenstone, saline to hypersaline. Perched aquifers in some of the tertiary sand deposits, brackish to saline groundwater.	Alkaline red, loamy to clayey soils.[1]	Rises and low hills, broad valleys which lack defined watercourses. Local relief is approx. 80 m. Cleared for agriculture: 72%	~300 mm	Possible, although the clay soils may hinder infiltration of water on the floodplain.
	South Eastern Zone of Ancient Drainage	Underlain by Archean granitoids of the Yilgarn Craton	Local to intermediate groundwater flow systems. Saprolite aquifers yielding saline groundwater (trending to acidic in the north). Groundwater in palaeochannels is low yielding because of fine quartz sediment. Saline to hypersaline.	Hillslopes and crests: Gravelly sandplain and sandy earth. Mid-slopes to valley floor: loamy duplex to loamy earths to calcareous clays. Regolith ~ 30 m thick.	Undulating plain dominated by salt lake chains in main valleys.[1] Valleys are broad and flat (5-8 km) with extensive palaeodrainages Cleared: 69%	~300-350 mm	Unlikely. Low-relief, low rainfall.
	South Western Zone of Ancient Drainage	Underlain by Archean granitoids of the Yilgarn Craton	Local groundwater system in low-permeability saprolite and palaeochannel aquifers. Mostly saline.	Shallow sandy/loamy duplex soils. Sandy gravels in uplands. Prone to waterlogging or inundation throughout winter.	Ancient, gently undulating plateau with local relief 10-40 m. Salt lake chains associated with sluggish drainage system. Broad alluvial plains and valleys. Palaeochannels in larger valleys, with extensive flow paths. Cleared: 86%	~300-350 mm	Unlikely. Low rainfall, mod-high salinity risk.

Hydrozone		Geology	Hydrogeology	Soils	Landform	Climate [2]	NSF Applicable
	Albany Sandplain	Underlain by Tertiary marine sediments overlying Proterozoic granitic and metamorphic rocks	West: Local and intermediate groundwater flow systems that discharge into surface drainage. East: Intermediate to regional groundwater flow systems with very little lateral flow. Many lakes.	Sandy duplexes with some sands and gravels.	Gently undulating plain dissected by short rivers. Broad plains with lakes and depressions that become seasonally inundated. Cleared: 51%	~400-550 mm	Possible. Due to the presence of local groundwater flow systems in the western portion, and sandy, coarse-grained substrate.
	Stirling Range	Quaternary sediments underlain by granitoids of the Yilgarn Craton	Underlying aquifers are stagnant and one-dimensional due to low gradient and low hydraulic conductivity of the regolith. Groundwater is saline to extremely saline.	Rocky and gravelly soils on the mountains; sandy duplexes on the rises and plain. Regolith is >100m thick in some portions of the Basin.	Steep mountains of the Stirling Range, undulating rises; broad, poorly drained plains with salt lakes (North Stirling Basin).	~300 mm	Unlikely. The depth of the regolith profile combined with the high transmissivity of gravelly soils, is unlikely to provide adequate storage for rehydration of the landscape.
	Pallinup	Underlain by Archean granitoids of the Yilgarn Craton	Local to intermediate aquifers, discharge into surface drainage and tributaries. Low hill areas, groundwater gradients facilitate flow into creeklines and valley floors. Lower aquifer storage capacity due to shallow to moderate regolith thickness (5-20 m). Mainly saline groundwater.	Shallow sandy duplex soils, sodic and alkaline clay subsoils.	Undulating rises and low hills. Well-defined creeklines. Pallinup River is the main drainage line. Cleared for agriculture: 85%	~300 mm	Possible, however low rainfall area, and moderate salinity risk.
	Jerramungup Plain	Eocene marine sediments overlying Proterozoic granitic and metamorphic rocks	Local groundwater flow systems in dissected valleys with shallower (5-12 m) regolith. Local to intermediate groundwater systems in broader valleys with gentle incline (1-3%) and moderate regolith thickness (10-30 m). Predominantly saline.	Alkaline sandy duplex soils with some clays, sands and gravels.	Level to gently undulating plain dissected by short rivers. Cleared: 61%	~250-400 mm	Possible, however low rainfall area, and moderate salinity risk.

Hydrozone		Geology	Hydrogeology	Soils	Landform	Climate [2]	NSF Applicable
	Ravensthorpe	Underlain by Precambrian basement rocks intruded by Proterozoic mafic dykes in the north	Local groundwater flow systems due to disconnected aquifers. These discharge into low-lying areas (waterways, wetlands), or form hillside seeps.	Alkaline sandy duplex soils with some sands and gravels.	Rolling to undulating low hills formed on fractured and weathered basement rocks. Moderately dissected with south-flowing rivers.[1] Cleared for agriculture: 20%	~350-450 mm	Possible, however low rainfall area, and moderate salinity risk.
	Esperance Sandplain	Eocene marine sediment overlying Proterozoic granitic and metamorphic rocks of the Albany-Fraser Orogen	Local to intermediate groundwater flow systems in areas with well-defined external drainage. Intermediate to regional groundwater flow systems where drainage is internal and poorly defined. Groundwater flow within basement and overlying sediments is sluggish due to the low groundwater gradient (<1%). Potential for perched localised aquifers in areas with deep sands.	Fine sandy duplex soils and fine sands.	Level to gently undulating sandplain dissected by short rivers flowing south. Poorly defined drainage systems flow into freshwater swamps. Cleared for agriculture: 65%	~300-400 mm	Possible, however low rainfall area, and moderate salinity risk.
	Salmon Gums Mallee	Tertiary sediments underlain by Proterozoic granites	Predominantly intermediate groundwater flow systems. North-west has localised groundwater flow systems in areas of undulating basement. Saline to extremely saline.	Alkaline grey sandy duplexes that overlie marine sediments.	Level to gently undulating plain with numerous salt lakes.	~450-600 mm	Possible, however low rainfall area, and moderate salinity risk.

Hydrozone		Geology	Hydrogeology	Soils	Landform	Climate [2]	NSF Applicable
Zone of Rejuvenated Drainage (Largely Cleared)	Northern & Southern Zone of Rejuvenated Drainage	Underlain by Archean granitoids of the Yilgarn Craton	Local groundwater flow systems (saprolite aquifers between weathered profile and basement). Saline near drainage lines. Perched aquifers of low salinity, but limited supply.	Soils formed in colluvium or rock weathered in-situ. Deep sandy duplex soils on slopes and valley flats.	Gently undulating rises to low hills; continuous stream channels that flow in most years. Broad valley floors. Cleared for dryland agriculture: 87% (northern); 78% (southern)	~300-450 mm	Unlikely (aside from areas of upland sandplains and thin regolith).
	Eastern Darling Range	Underlain by Archean granitoids of the Yilgarn Craton	Local (and occasionally intermediate) groundwater flow systems. Discharge in drainage lines and on valley floors in cleared catchments. Brackish to saline groundwater.	Ranging from sandy gravels and sands, to loamy soils and sandy duplexes on the valley slopes.	Undulating to rolling terrain, local relief 20-100 m. Many narrow valley floors incised into underlying basement rock. Broad (1-3 km), shallow valleys with poorly drained flats. Cleared for agriculture: 55%	~500-600 mm	Unlikely.
Zone of Rejuvenated Drainage, Darling Range, Minimal Clearance	Western Darling Range	Underlain by Archean granitoids of the Yilgarn Craton	Local or occasionally intermediate groundwater systems. Discharge in drainage lines and on valley floors in cleared catchments. Predominantly brackish.	Loamy and sandy gravels, with small areas of deep sands.	Undulating lateritic plateau, deeply incised valleys. Native forest dominates: 78%	~650-900 mm	Possible.
	Warren-Denmark Southland	Deeply weathered granite and gneiss overlain by Tertiary and Quaternary sediments in the south	Local groundwater systems facilitated by doleritic dykes and shear zones in places. Low quality groundwater – brackish to saline.	Loamy gravel, duplex sandy gravel, wet and semi-wet soil.	Topography rises in a series of broad benches. Clearance for agriculture: 25%	~450-1100 mm	Likely.

Hydrozone		Geology	Hydrogeology	Soils	Landform	Climate [2]	NSF Applicable
Perth Basin	Kalbarri Sandplain	Occurs within the Carnarvon Basin, dominant geological unit is the Tumblagooda Sandstone	Surficial aquifer underlain by intermediate to regional GW flow system (in Tumblagooda Sandstone). Good connectivity, behaves as single aquifer. Discharge to Indian Ocean. Fresh.	Red shallow sands with deep sands, stony soils and calcareous deep sands. [1]	Undulating plateau or sandplains. Moderately dissected valleys and some gorges. Alluvial plains dominate close to coast.	~350 mm	Unlikely. Low relief, local groundwater system not present. Low rainfall area.
	Northampton Bock	Underlain by the Northampton Block Proterozoic crystalline gneissic basement rock	Saprolite hosts local groundwater flow systems. Groundwater predominantly from underlying fractured basement. Groundwater-surface water discharge via Chapman River. Palaeochannel associated with River contains 19 m alluvial channel sediments. Alluvial channel sediments host an intermediate GW system.	Gritty clay saprolite (deep sands with shallow loamy duplexes). Shallow gravels.	Dissected lateritic terrain (hills, sandplains, breakaways and plateaux).	~300-350 mm	Possible.
	East Binnu Sandplain	Occurs within Coolcalalaya Sub-basin, underlain by Tumblagooda Sandstone	Intermediate to regional GW system in Tumblagooda Sandstone. Discharge to Murchison River. Brackish to saline groundwater.	Deep sands with hardpan shallow loams. Overlying sandplain formed by in-situ weathering of the sandstone.	Gently undulating, internally draining, sandplain plateau.	~250-300 mm	Unlikely.
	Irwin Terrace	Alluvial valley plains in the south underlain by Proterozoic granulites Permian and Jurassic sediments [1]	Outcropping of local aquifers including the Nangetty Formation, High Cliff Sandstone and Irwin River Coal measures. Brackish to saline groundwater.[3]	Permian sediments, clayey to silty soils. Heavy clay has low hydraulic conductivity. Where exposed in drainage lines, severely salt-affected.	South: dissected terrain with breakaways and plateau remnants. Alluvial valley plains. North: Wash plains surrounded by undulating sandplain. Cleared for agriculture: 83%	~250-350 mm	Unlikely. The clay soils would hinder infiltration of water on the floodplain.

Hydrozone		Geology	Hydrogeology	Soils	Landform	Climate [2]	NSF Applicable
	Arrowsmith	Sediments overlying the interbedded felspathic sandstone, siltstone and claystone of the Yarragadee Formation	Regional groundwater system in unconfined aquifer in Yarragadee Formation. Low salinity. Discharge to Indian Ocean.	Sandy and gravelly soils formed in colluvium and rock weathered in-situ.[1]	Gently undulating sandplain and sandy alluvial fans on the Eneabba Plain. Low hills (Tamala Limestone). Cleared for agriculture: 63%	~300-500 mm	Unlikely if local groundwater system is absent.
	Dandaragan Plateau	Cretaceous sediments overlying the Parmelia Formation (felspathic sandstone, with minor siltstone and claystone)	Regional groundwater system in unconfined Parmelia Formation aquifer. Localised, perched aquifers occur (not widespread).	Lateritic plateau. Red, brown and yellow deep sands, sandy gravels, duplexes and clays.[4]	Gently undulating plateau with areas of sandplain and some laterite. Broad u-shaped valleys (80-150 m deep). [1]	~300-500 mm	Unlikely if local groundwater system is absent.
	Coastal Plain	Unconsolidated sediments and limestone over sedimentary rocks	Highly permeable regional aquifers in Leederville, Yarragadee and Cockleshell Gully Formations. Yoganup Formation is major recharge area for the aquifers. Fresh to saline groundwater.	Soil progression from west to east: Deep sands (calcareous), semi-wet sands (non-calcareous) in low-lying wet areas, clayey to sandy alluvial soils with wet areas.[1]	Fixed dunes immediately inland from coast. Flat to gently undulating plain, low-lying wet areas further from coast. Cleared for dryland or irrigated agriculture: 36%	~500-850 mm	Possible in some areas where salinity won't be exacerbated.
	Donnybrook Sunkland	Deeply weathered mantle and colluvium over Perth Basin sedimentary rocks	Surficial aquifer limited to small pockets of alluvium and old palaeochannels. Unconfined Leederville underlies the surficial aquifer. Fresh.	Duplex sandy gravels, wet and semi-wet soils, deep sands and loamy gravels. Poorly drained sandy alluvium plain in the south.	Moderately dissected lateritic plateau. Less than 10% clearance	~650-900 mm	Likely.

	Leeuwin	Granite overlain by Tamala Limestone	Surficial aquifer in thick alluvial and colluvial deposits. Saturation is limited.	Loamy gravels, duplex sandy gravels, wet and semi-wet soils, calcareous deep sand and loams.	Coastal sand dunes and moderately dissected lateritic plateau. Less than 44% cleared for agriculture.	~1000 mm	Likely.
	Scott Coastal Plain	Limestone and unconsolidated sediments over sedimentary rocks	Limestone and unconsolidated sediments over sedimentary rocks.	Acidic, non-calcareous sands dominate the low-lying wet areas.	Coastal sand dunes and plains with swamps.	~900-1000 mm	Likely.

Notes:

Unless otherwise indicated, the primary document referenced is:

Raper, G., Speed, R., Simons, J., Killen, A., Blake, A., Ryder, A., Bourke, L. (2014). *Groundwater trend analysis for south-west Western Australia 2007–12*. (Resource management technical report 388). Western Australia, Perth: Department of Agriculture and Food

Additional references consulted are denoted as follows:

[1] Purdie, B. R., Tille, P. J., & Schoknecht, N. R. (2004). *Soil-landscape mapping in south-Western Australia: an overview of methodology and outputs.* (Report 280). Western Australia, Perth: Department of Agriculture and Food

[2] McFarlane, D., George, R., Ruprecht, J., Charles, S., & Hodgson, G. (2020). Runoff and groundwater responses to climate change in South West Australia. *Journal of the Royal Society of Western Australia, 103*, 9-27

[3] Le Blanc Smith, G., & Mory, AJ. (1995). *Geology and Permian coal resources of the Irwin Terrace, Perth Basin, Western Australia.* (Report 44). Western Australia, Perth: Western Australia Geological Survey

[4] Griffin, EA., Stuart-Street, A., van Wyk, L., & Tille, PJ. (2019). *Soil capability assessment for expanding irrigated agriculture in the Dinner Hill focus area, Midlands, Western Australia*. (Report 406). Western Australia, Perth: Department of Primary Industries and Regional Development

Table 4: Likely risks for each hydrozone resulting from NSF methods, considered in relation to wind and water erosion, soil acidity, soil organic carbon, soil compaction, water repellence and dryland salinity.

Hydrozone		Soil Acidity	Wind Erosion	Water Erosion	Soil Organic Carbon	Soil Compaction	Water Repellence	Dryland Salinity
Wheatbelt: Zone of Ancient Drainage (Largely Cleared)	Northern Zone of Ancient Drainage	Current condition / trend: Poor but variable (Central Northern Wheatbelt) and deteriorating (Mullewa to Morawa).	Current hazard / trend: Very high and variable (Central Northern Wheatbelt) and moderate and variable (Mullewa to Morawa).	Current hazard / trend: Low and stable.	Current abundance: Low-moderate.	Current hazard / trend: High and deteriorating due to presence of red soils which are prone to crusting and forming hard pans on cropped soils.	Current condition / trend: Fair-good and stable.	Extent, risk and groundwater trends: Salinity is extensive and continuing to expand. Risk is moderate as expansion is slower than in the past. Variable trends in groundwater levels.
	Southern Cross	Current condition / trend: Poor but variable (Central Northern Wheatbelt) and deteriorating (Mullewa to Morawa).	Current hazard / trend: Very high and variable (Central Northern Wheatbelt) and moderate and variable (Mullewa to Morawa).	Current hazard / trend: Low and stable.	Current abundance: Low-moderate.	Current hazard / trend: High and deteriorating due to presence of red soils which are prone to crusting and forming hard pans on cropped soils.	Current condition / trend: Fair-good and stable.	Extent, risk and groundwater trends: Moderate salinity extent. Low risk of salinity expansion with falling groundwater levels.
	South Eastern Zone of Ancient Drainage	Current condition / trend: Poor and deteriorating.	Current hazard / trend: Low and variable.	Current hazard / trend: Low and deteriorating.	Current abundance: Moderate.	Current hazard / trend: High and deteriorating.	Current condition / trend: Fair and stable.	Extent, risk and groundwater trends: Salinity is extensive, continuing to expand. Risk is moderate due to slower rate of expansion. Groundwater trends are variable.
	South Western Zone of Ancient Drainage	Current condition / trend: Poor and deteriorating.	Current hazard / trend: Low and variable.	Current hazard / trend: Low and deteriorating.	Current abundance: Moderate.	Current hazard / trend: High and deteriorating.	Current condition / trend: Fair and stable.	Extent, risk and groundwater trends: Salinity is extensive, continuing to expand. Risk is high and groundwater levels are rising.
	Albany Sandplain	Current condition / trend: Very poor and deteriorating.	Current hazard / trend: Very low and variable.	Current hazard / trend: Low and deteriorating.	Current abundance: Low-moderate.	Current hazard / trend: Moderate and stable.	Current condition / trend: Very poor and stable.	Extent, risk and groundwater trends: Salinity extent is minor, risk is low with variable trends in deep groundwater.

Hydrozone		Soil Acidity	Wind Erosion	Water Erosion	Soil Organic Carbon	Soil Compaction	Water Repellence	Dryland Salinity
	Stirling Range	Current condition / trend: Poor but stable. Some areas improving.	Current hazard / trend: Low and variable.	Current hazard / trend: Low and deteriorating.	Current abundance: Moderate.	Current hazard / trend: High and deteriorating (due to increased cropping).	Current condition / trend: Poor and stable.	Extent, risk and groundwater trends: Salinity is extensive, and risk of expansion is low as equilibrium will be reached in the short term. Groundwater trends are variable.
	Pallinup	Current condition / trend: Poor and deteriorating.	Current hazard / trend: Low and variable.	Current hazard / trend: Low and deteriorating.	Current abundance: Moderate.	Current hazard / trend: High and deteriorating.	Current condition / trend: Fair and stable.	Extent, risk and groundwater trends: Extent of salinity is moderate, overall risk is moderate as expansion is likely but extent is restricted. Variable groundwater trends.
	Jerramungup Plain	Current condition / trend: Poor but stable. Some areas improving.	Current hazard / trend: Low and variable.	Current hazard / trend: Low and deteriorating.	Current abundance: Moderate.	Current hazard / trend: High and deteriorating (due to increased cropping).	Current condition / trend: Poor and stable.	Extent, risk and groundwater trends: Salinity extent is moderate, with moderate risk of expansion which is occurring slowly and likely to continue. Mostly rising trends in groundwater levels.
	Ravensthorpe	Current condition / trend: Poor but stable. Some areas improving.	Current hazard / trend: Low and variable.	Current hazard / trend: Low and deteriorating.	Current abundance: Moderate.	Current hazard / trend: High and deteriorating (due to increased cropping).	Current condition / trend: Poor and stable.	Extent, risk and groundwater trends: Salinity extent is minor, with moderate risk of expansion which is likely but extent restricted. Mostly rising groundwater levels.
	Esperance Sandplain	Current condition / trend: Very poor and deteriorating.	Current hazard / trend: Very low and variable.	Current hazard / trend: Low and deteriorating.	Current abundance: Low-moderate.	Current hazard / trend: Moderate and stable.	Current condition / trend: Very poor and stable.	Extent, risk and groundwater trends: Extent of salinity is moderate; high risk of expansion due to rising groundwater levels.
	Salmon Gums Mallee	Current condition / trend: Good and stable - due to presence of alkaline and calcareous soils.	Current hazard / trend: High and variable.	Current hazard / trend: Low and stable.	Current abundance: Moderate.	Current hazard / trend: Moderate and stable.	Current condition / trend: Good and stable.	Extent, risk and groundwater trends: Salinity extent is moderate; risk of expansion is moderate (possible) due to rising groundwater levels.

Hydrozone		Soil Acidity	Wind Erosion	Water Erosion	Soil Organic Carbon	Soil Compaction	Water Repellence	Dryland Salinity
Zone of Rejuvenated Drainage (Largely Cleared)	Northern & Southern Zone of Rejuvenated Drainage	Current condition / trend: Poor and deteriorating.	Current hazard / trend: Moderate and variable.	Current hazard / trend: Moderate and stable.	Current abundance: Moderate.	Current hazard / trend: Moderate and stable.	Current condition / trend: Poor and deteriorating.	Extent, risk and groundwater trends: Salinity is extensive (southern zone) with mostly stable groundwater levels. Salinity is moderate (Northern zone) with variable trends in groundwater. Both zones are considered moderate risk of salinity expansion.
	Eastern Darling Range	Current condition / trend: Very poor and deteriorating.	Current hazard / trend: Moderate and variable.	Current hazard / trend: Low and stable.	Current abundance: Moderate-high.	Current hazard / trend: Low and stable.	Current condition / trend: Poor and deteriorating.	Extent, risk and groundwater trends: Salinity extent is moderate. Risk is moderate and groundwater levels mostly stable.
Zone of Rejuvenated Drainage, Darling Range, Minimal Clearance	Western Darling Range	Current condition / trend: Very poor and deteriorating.	Current hazard / trend: Moderate and variable.	Current hazard / trend: Low and stable.	Current abundance: Moderate-high.	Current hazard / trend: Low and stable.	Current condition / trend: Poor and deteriorating.	Extent, risk and groundwater trends: Salinity extent is minor, low risk of expansion due to falling groundwater levels.
	Warren-Denmark Southland	Current condition / trend: Very poor and deteriorating.	Current hazard / trend: Moderate and variable.	Current hazard / trend: Low and stable.	Current abundance: Moderate-high.	Current hazard / trend: Low and stable.	Current condition / trend: Poor and deteriorating.	Extent, risk and groundwater trends: Salinity extent is minor, with moderate risk of expansion depending on future land use. Variable groundwater trends.

Hydrozone		Soil Acidity	Wind Erosion	Water Erosion	Soil Organic Carbon	Soil Compaction	Water Repellence	Dryland Salinity
Perth Basin	Kalbarri Sandplain	Current condition / trend: Poor but improving.	Current hazard / trend: Very low and variable.	Current hazard / trend: Moderate and deteriorating.	Current abundance: Low.	Current hazard / trend: High and deteriorating.	Current condition / trend: Poor and deteriorating.	Extent, risk and groundwater trends: Salinity extent is minor; risk of salinity development is moderate; variable groundwater trend.
	Northampton Bock	Current condition / trend: Poor but improving.	Current hazard / trend: Very low and variable.	Current hazard / trend: Moderate and deteriorating.	Current abundance: Low.	Current hazard / trend: High and deteriorating.	Current condition / trend: Poor and deteriorating.	Extent, risk and groundwater trends: Salinity extent is minor. Low risk of expansion; mostly rising groundwater trends.
	East Binnu Sandplain	Current condition / trend: Poor but improving.	Current hazard / trend: Very low and variable.	Current hazard / trend: Moderate and deteriorating.	Current abundance: Low.	Current hazard / trend: High and deteriorating.	Current condition / trend: Poor and deteriorating.	Extent, risk and groundwater trends: Salinity extent is minor; high risk of salinity developing in medium term due to rising groundwater levels.
	Irwin Terrace	Current condition / trend: Poor but improving.	Current hazard / trend: Very low and variable.	Current hazard / trend: Moderate and deteriorating.	Current abundance: Low.	Current hazard / trend: High and deteriorating.	Current condition / trend: Poor and deteriorating.	Extent, risk and groundwater trends: Salinity extent is moderate; moderate risk of expansion; variable trends in groundwater.
	Arrowsmith	Current condition / trend: Poor but stable. Some improvement.	Current hazard / trend: Very low and variable.	Current hazard / trend: Low and stable.	Current abundance: Low.	Current hazard / trend: Moderate and stable.	Current condition / trend: Very poor and stable.	Extent, risk and groundwater trends: Salinity extent is minor; low risk of salinity development in medium term; variable trends in groundwater levels.
	Dandaragan Plateau	Current condition / trend: Poor but stable. Some improvement.	Current hazard / trend: Very low and variable.	Current hazard / trend: Low and stable.	Current abundance: Low.	Current hazard / trend: Moderate and stable.	Current condition / trend: Very poor and stable.	Extent, risk and groundwater trends: Salinity extent is minor; high risk of expansion with mostly rising groundwater levels.
	Coastal Plain	Current condition / trend: Very poor and deteriorating.	Current hazard / trend: Not assessed.	Current hazard / trend: Low and stable.	Current abundance: High-very high.	Current hazard / trend: Low and stable.	Current condition / trend: Very poor and stable.	Extent, risk and groundwater trends: Salinity extent is minor,

Hydrozone		Soil Acidity	Wind Erosion	Water Erosion	Soil Organic Carbon	Soil Compaction	Water Repellence	Dryland Salinity
								with low risk and mostly stable groundwater trends.
	Donnybrook Sunkland	Current condition / trend: Very poor and deteriorating.	Current hazard / trend: Not assessed.	Current hazard / trend: Low and stable.	Current abundance: High-very high.	Current hazard / trend: Low and stable.	Current condition / trend: Very poor and stable.	Extent, risk and groundwater trends: Salinity extent is minor, with very low risk of expansion due to the zone reaching hydrological equilibrium.
	Leeuwin	Current condition / trend: Very poor and deteriorating.	Current hazard / trend: Not assessed.	Current hazard / trend: Low and stable.	Current abundance: High-very high.	Current hazard / trend: Low and stable.	Current condition / trend: Very poor and stable.	Extent, risk and groundwater trends: Salinity extent is minor, with very low risk of expansion due to the zone reaching hydrological equilibrium.
	Scott Coastal Plain	Current condition / trend: Very poor and deteriorating.	Current hazard / trend: Not assessed.	Current hazard / trend: Low and stable.	Current abundance: High-very high.	Current hazard / trend: Low and stable.	Current condition / trend: Very poor and stable.	Extent, risk and groundwater trends: Salinity extent is minor, with very low risk of expansion due to the zone reaching hydrological equilibrium.

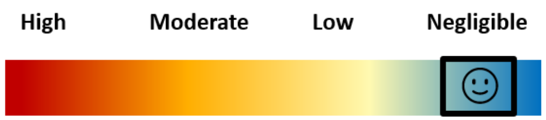
Notes:

Unless otherwise indicated, the primary document referenced is:

Department of Agriculture and Food (2013). Report card on sustainable natural resource use in agriculture. In. Western Australia: Department of Agriculture and Food.

Table 5: Wind Erosion Risk from NSF

Risk: Wind Erosion

Hydrozone	Current trend (2013) [1]	Forecast Risk with NSF Interventions	
All hydrozones	Current trends across the SWWA region includes a very high risk of wind erosion in the Northern Zone of Ancient Drainage to very low risk along the south coast and north west coast.	Expect the risk of wind erosion as a result of implementation of NSF interventions to be negligible due to increased ground cover including extensive revegetation, mulching, and grazing controls. These interventions may ameliorate the wind erosion hazard factor in some hydrozones.	

Legend

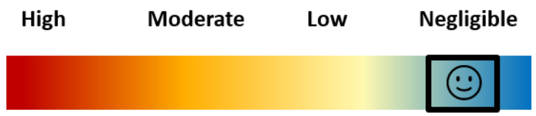
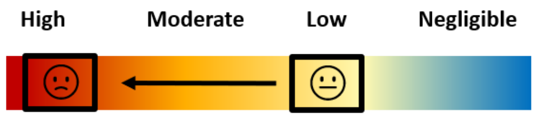
Negligible risk		☺	Natural Sequence Farming methods are likely to reduce the current risk level or improve resource condition
Low risk		😐	Natural Sequence Farming methods are unlikely to change current risk or lead to any changes in land condition or land degradation relative to current practices
Moderate risk		☹	Natural Sequence Farming methods are likely to potentially exacerbate current risk or lead to land degradation
High risk			

Note:

[1] Current trend data has been sourced from: Department of Agriculture and Food (2013). Report card on sustainable natural resource use in agriculture. In. Western Australia: Department of Agriculture and Food.

Table 6: Water Erosion Risk from NSF

Risk: Water Erosion

Hydrozone	Current trend (2013) [1]	Forecast Risk with NSF Interventions	
All hydrozones	Current trends of water erosion are generally low across the broader SWWA region.	**NSF intervention: Revegetation** Revegetation of the hillslopes, floodplain and riparian corridor as prescribed by NSF presents a negligible risk of exacerbating water erosion in the hydrozones across SWWA.	
		NSF Intervention: Contour banks and in-stream structures Construction of contour banks on the hillslopes and 'leaky weirs' in the active river channel are considered to present a low to moderate risk within the landscape. While both structures work to reduce surface water flow velocity (and thereby potentially ameliorate water erosion), if poorly constructed, these surface water structures may exacerbate water erosion.	

Legend

- Negligible risk
- Low risk
- Moderate risk
- High risk

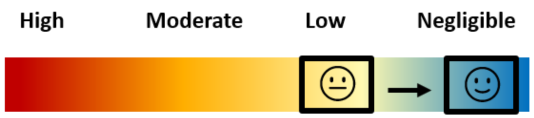
- ☺ Natural Sequence Farming methods are likely to reduce the current risk level or improve resource condition
- 😐 Natural Sequence Farming methods are unlikely to change current risk or lead to any changes in land condition or land degradation relative to current practices
- ☹ Natural Sequence Farming methods are likely to potentially exacerbate current risk or lead to land degradation

Note:

[1] Current trend data has been sourced from: Department of Agriculture and Food (2013). Report card on sustainable natural resource use in agriculture. In. Western Australia: Department of Agriculture and Food.

Table 7: Soil Acidity Risk from NSF

Risk: Soil Acidity

Hydrozone	Current trend (2013) [1]	Forecast Risk with NSF Interventions
All hydrozones	Current trends of soil acidity are generally very poor along the south and east coast of SWWA, with inland hydrozones generally poor (with 55-70% of soils below the target pH).	Overall, it's unlikely that NSF methods would contribute to exacerbation of soil acidity in SWWA. Soil acidity is caused through leaching of nitrates from the soil which may be accelerated by other risk factors like water erosion. Increased ground cover through NSF methods may then reduce leaching or potentially minimise loss of nutrients from the landscape. Thus, the risks attached to NSF are negligible with regards to soil acidity, and it may present as a means to manage soil acidity in the landscape. 

Legend

Negligible risk			Natural Sequence Farming methods are likely to reduce the current risk level or improve resource condition
Low risk			Natural Sequence Farming methods are unlikely to change current risk or lead to any changes in land condition or land degradation relative to current practices
Moderate risk			Natural Sequence Farming methods are likely to potentially exacerbate current risk or lead to land degradation
High risk			

Note:

[1] Current trend data has been sourced from: Department of Agriculture and Food (2013). Report card on sustainable natural resource use in agriculture. In. Western Australia: Department of Agriculture and Food.

Table 8: Soil Compaction Risk from NSF

Risk: Soil Compaction

Hydrozone	Current trend (2013) [1]	Forecast Risk with NSF Interventions
All hydrozones	Current trends of soil compaction severity are low (west) to high (east) across the broader SWWA region.	The risk of exacerbating soil compaction with implementation of NSF interventions is negligible. Rather, through restricting stock movement (as proposed by NSF) and revegetating the landscape to increase soil organic matter content and maintain soil structure, NSF methods may ameliorate some of the land degradation issues related to soil compaction in the landscape.

Legend

Negligible risk	Natural Sequence Farming methods are likely to reduce the current risk level or improve resource condition
Low risk	Natural Sequence Farming methods are unlikely to change current risk or lead to any changes in land condition or land degradation relative to current practices
Moderate risk	Natural Sequence Farming methods are likely to potentially exacerbate current risk or lead to land degradation
High risk	

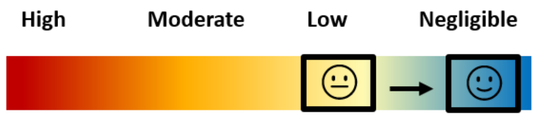
Note:

[1] Current trend data has been sourced from: Department of Agriculture and Food (2013). Report card on sustainable natural resource use in agriculture. In. Western Australia: Department of Agriculture and Food.

Table 9: Soil Organic Carbon Risk from NSF

Risk: Soil Organic Carbon

Hydrozone	Current trend (2013) [1]	Forecast Risk with NSF Interventions
All hydrozones	Current trends of soil organic carbon are high to very high on the Swan to Scott Coastal Plains, and low to moderate across the broader SWWA region.	Risks associated with depleting soil organic matter following implementation of NSF are negligible. Through revegetation of the hillslopes, floodplain and riparian corridor, plant biomass is being added to the landscape and will contribute to soil organic carbon stores. Notably, while the risk is low, the potential to ameliorate the current risk associated with low organic carbon stores is confined predominantly to higher rainfall areas which support increased biomass production .



Legend

	Negligible risk	☺	Natural Sequence Farming methods are likely to reduce the current risk level or improve resource condition
	Low risk	😐	Natural Sequence Farming methods are unlikely to change current risk or lead to any changes in land condition or land degradation relative to current practices
	Moderate risk	☹	Natural Sequence Farming methods are likely to potentially exacerbate current risk or lead to land degradation
	High risk		

Note:

[1] Current trend data has been sourced from: Department of Agriculture and Food (2013). Report card on sustainable natural resource use in agriculture. In. Western Australia: Department of Agriculture and Food.

Table 10: Dryland Salinity Risk from NSF

Risk: Dryland Salinity

Hydrozone	Current trend (2013) [1]	Forecast Risk with NSF Interventions	
Kalbarri Sandplain	Salinity extent is minor; risk of salinity development is moderate; variable groundwater trend.	Rehydration of the landscape using NSF physical structure interventions may potentially promote development of salinity on the Kalbarri sandplain.	High Moderate Low Negligible 
Northampton Block	Salinity extent is minor. Low risk of expansion; mostly rising groundwater trends.	Rehydration of the landscape using NSF physical structure interventions coupled with rising groundwater trends may potentially promote development of salinity in the Northampton Block hydrozone.	High Moderate Low Negligible 

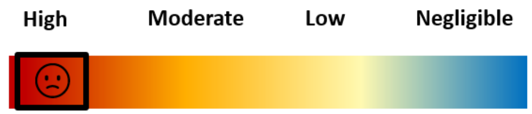
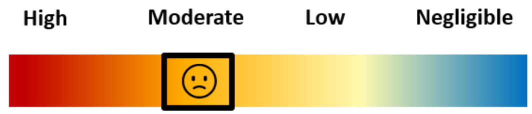
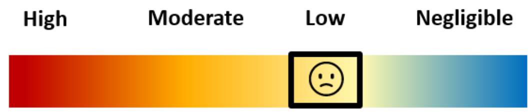
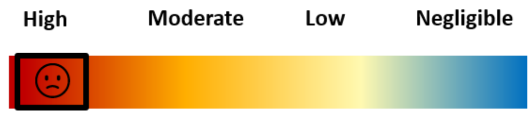
Legend

Negligible risk	Natural Sequence Farming methods are likely to reduce the current risk level or improve resource condition
Low risk	Natural Sequence Farming methods are unlikely to change current risk or lead to any changes in land condition or land degradation relative to current practices
Moderate risk	Natural Sequence Farming methods are likely to potentially exacerbate current risk or lead to land degradation
High risk	

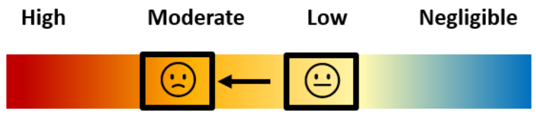
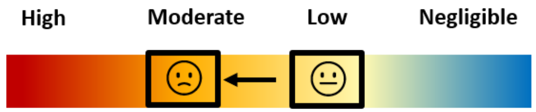
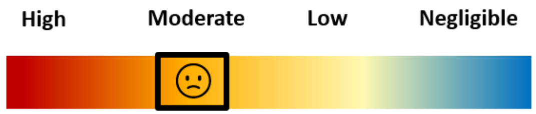
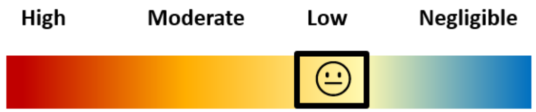
Note:

[1] Current trend data has been sourced from: Department of Agriculture and Food (2013). Report card on sustainable natural resource use in agriculture. In. Western Australia: Department of Agriculture and Food.

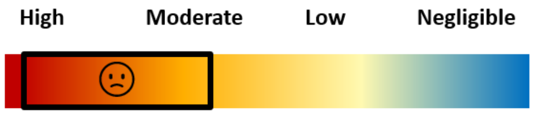
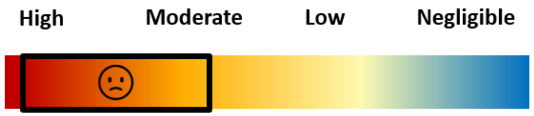
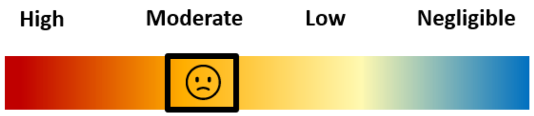
Risk: Dryland Salinity

Hydrozone	Current trend (2013) [1]	Forecast Risk with NSF Interventions	
East Binnu Sandplain	Salinity extent is minor; high risk of salinity developing in medium term due to rising groundwater levels.	The risk that NSF methods would promote dryland salinity within the East Binnu Sandplain hydrozone is considered to be high. Rehydration works would cause the groundwater table (at depth of approximately 10 m below ground level (bgl)) to rise further, posing a risk to the low-lying plains.	
Irwin Terrace	Salinity extent is moderate; moderate risk of expansion; variable trends in groundwater.	The risk of salinity developing as a result of NSF rehydration work is considered to be moderate.	
Arrowsmith	Salinity extent is minor; low risk of salinity development in medium term; variable trends in groundwater levels.	Risk of salinity developing is low, and likely to be localised in areas where the perched groundwater tables overlie the regional groundwater system. NSF rehydration works will therefore have a localised impact, if any. The area is also low productive quality, and therefore the consequences of salinity development are also relatively minor. [1]	
Dandaragan Plateau	Salinity extent is minor; high risk of expansion with mostly rising groundwater levels.	Expanding salinity in this area of high quality agricultural land as a result of rising groundwater tables (less than 10 m bgl) means that the risks associated with rehydration of the landscape is also high. [1]	

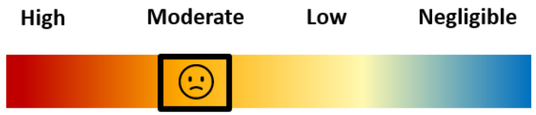
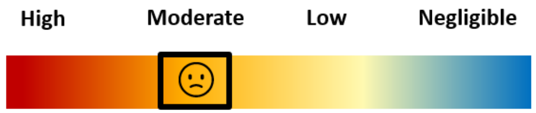
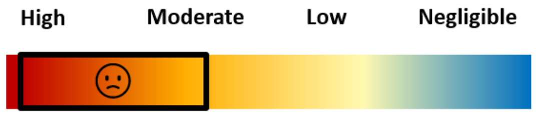
Risk: Dryland Salinity

Hydrozone(s)	Current trend (2013) [1]	Forecast Risk with NSF Interventions	
Coastal Plain	Salinity extent is minor, with low risk and mostly stable groundwater trends.	Low-moderate salinity risk associated with NSF rehydration work depending on where methods are implemented. The area is underlain by a shallow surficial aquifer which could be subject to recharge via landscape wetting. Some areas are of poor drainage and more prone to salinisation, however these are unlikely to be used for production. [1]	
Donnybrook Sunkland Leeuwin Scott Coastal Plain	Salinity extent is minor, with very low risk of expansion due to the zone(s) reaching hydrological equilibrium.	Risk of salinity is low in these areas, however NSF rehydration works have potential to disrupt the hydrological equilibrium, potentially inducing salinity in the medium-term.	
Northern Zone of Ancient Drainage	Salinity is extensive and continuing to expand. Current risk is moderate as expansion is slower than in the past. Variable trends in groundwater levels.	Rehydration of the landscape is likely to present a moderate risk in this landscape.	
Southern Cross	Moderate salinity extent. Low risk of salinity expansion with falling groundwater levels.	Groundwater levels are deep and falling and thus NSF rehydration works present a low risk in the Southern Cross hydrozone, but with high uncertainty. [1]	

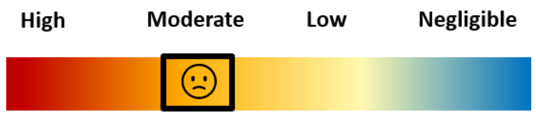
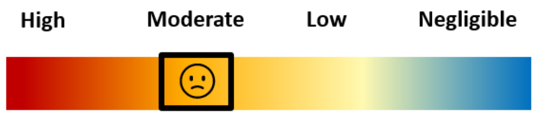
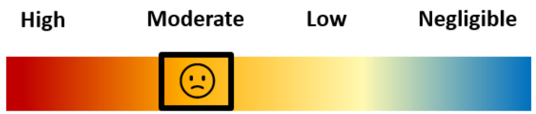
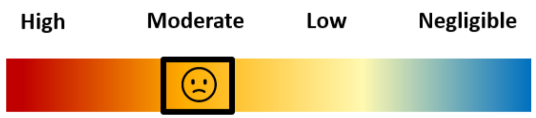
Risk: Dryland Salinity

Hydrozone	Current trend (2013) [1]	Forecast Risk with NSF Interventions	
South Eastern Zone of Ancient Drainage	Salinity is extensive, continuing to expand. Risk is moderate due to slower rate of expansion. Groundwater trends are variable.	Predicted salinity risk with NSF rehydration is moderate-high. There is potential that deliberate wetting of the landscape will accelerate salinity expansion in the landscape.	
South Western Zone of Ancient Drainage	Salinity is extensive, continuing to expand. Risk is high and groundwater levels are rising.	Predicted salinity risk with NSF rehydration is moderate-high. There is potential that deliberate wetting of the landscape will accelerate salinity expansion in the landscape.	
Albany Sandplain	Salinity extent is minor, risk is low with variable trends in deep groundwater.	Forecast risk from NSF rehydration works assessed to be low-moderate based on depth of groundwater, and that large areas of the Albany Sandplain are used as forestry plantations. [1]	
Stirling Range	Salinity is extensive, and risk of expansion is low as equilibrium will be reached in the short term. Groundwater trends are variable.	Risk of salinity is moderate with implementation of NSF rehydration works. It is considered that further salinity development is unlikely with the system reaching equilibrium, however it's unclear the impact of rehydration works on potentially disrupting this equilibrium with recharge to the shallow groundwater table. [1]	

Risk: Dryland Salinity

Hydrozone	Current trend (2013) [1]	Forecast Risk with NSF Interventions	
Pallinup	Extent of salinity is moderate, overall risk is moderate as expansion is likely but extent is restricted. Variable groundwater trends.	Forecast risk of NSF rehydration is moderate in the Pallinup hydrozone, depending on where it is applied in the landscape.	
Jerramungup Plain	Salinity extent is moderate, with moderate risk of expansion which is occurring slowly and likely to continue. Mostly rising trends in groundwater levels.	NSF rehydration works are likely to present a moderate risk within the Jerramugup Plain hdyrozone.	
Ravensthorpe	Salinity extent is minor, with moderate risk of expansion which is likely but extent restricted. Mostly rising groundwater levels.	The risk is moderate-high with implementation of NSF rehydration approach. There may be exacerbation of existing salinity by hillside seeps and at discharge points in the river channel, with potential to impact biodiversity along waterways in the Fitzgerald River National Park. [1]	
Esperance Sandplain	Extent of salinity is moderate; high risk of expansion due to rising groundwater levels.	Shallow, rising groundwater levels in an area already impacted by salinity places a moderate-high risk on NSF rehydration works undertaken within this hydrozone. Expanding salinity could potentially impact nearby productive agricultural land and proximity of Ramsar wetlands and national parks. [1]	

Risk: Dryland Salinity

Hydrozone	Current trend (2013) [1]	Forecast Risk with NSF Interventions	
Salmon Gums Mallee	Salinity extent is moderate; risk of expansion is moderate (possible) due to rising groundwater levels.	Predicted risk with NSF interventions is moderate due to rising groundwater tables in some areas.	
Northern & Southern Zone of Rejuvenated Drainage	Salinity is extensive (southern zone) with mostly stable groundwater levels. Salinity is moderate (Northern zone) with variable trends in groundwater. Both zones are considered moderate risk of salinity expansion.	Shallow groundwater tables with a rising trend in some instances may be at moderate risk with implementation of NSF rehydration works. Changes in climate may reduce the impact.	
Eastern Darling Range	Salinity extent is moderate. Risk is moderate and groundwater levels mostly stable.	Moderate risk associated with NSF rehydration work in Eastern Darling Range hydrozone.	
Western Darling Range	Salinity extent is minor, low risk of expansion due to falling groundwater levels.	Low salinity risk for NSF rehydration works in Western Darling Range hydrozone. The area is forested, with falling groundwater levels.	

Summary

NSF presents range of opportunities including reducing wind erosion hazard and increasing soil organic carbon but comes with risks in some landscapes from dryland salinity. The landscape of SWWA is very different to the Hunter region of NSW where NSF ideas originated. Across most landscapes in SWWA, water ponding and retention is a cause of waterlogging and salinity. Runoff in SWWA that could be potentially used to rehydrate a landscape is more episodic, absent for large periods of the year and in some locations is saline. The wheatbelt of WA experiences high evaporative potential and low summer rainfall, unlike the Hunter region of NSW where rainfall peaks in summer/autumn. Many of the production benefits of NSF go against the main trends seen in the SWWA agriculture zone, which includes removal of infrastructure that makes GPS-steer controlled-traffic operations less efficient, and a reduction in livestock numbers and the number of mixed (crop & livestock) operations. There is also a legacy of programs like WISALTS and deep drainage that have ultimately proved ineffective, uneconomic and not widely adopted. There are significant reputational risks in promoting a farming system that proposes to use one third of the land area for production and promises a ten-fold increase in production by retaining the soil at field capacity. Promoting NSF runs counter to understandings within the broader WA farming community based on their own experiences and multi-decade narrative from State agriculture agencies (supported by the science), that water ponding and salt waterlogging is a major risk to production and development of salinity.

Based on the criteria presented by the CSIRO expert panel, recommendations in the ARC Linkage Report, and this review of case studies and interviews with knowledge holders, it appears that NSF is only suitable for application to the higher rainfall (>600 mm) zone, and with caution in the higher gradient and more connected and rejuvenated landscapes of SWWA with low salinity risk (thin regolith and sandplain systems) in moderate rainfall (>350 mm) zones. This includes hydrozones on the south west and south coast. These are effectively higher rainfall SWWA landscapes that have a low salt store and low risk of salinity.

While the most suitable areas are those with lower salinity risks, these catchments are typically subject to DWER guidelines regarding structure construction, water allocations and related issues and governance restrictions that may impact NSF interventions. Based on the range of available case studies, NSF appears most commonly associated with smaller-scale primary production including equestrian and livestock production, often supported from off-farm income or other financial support or subsidy.

There are no case studies identified to support the application of NSF as a holistic package to broadacre cropping operations in the grainbelt. The approach of NSF to cropping only 1/3 of the land is identified as not financially viable through the SWWA grainbelt. Some components of NSF and other regenerative practices may have an important role to play in addressing issues such as use of low-productivity and saline areas of the lower rainfall and gradient parts wheatbelt.

In summary, for the main broadacre farming areas within SWWA is not considered financially viable for implementing NSF as described by Peter Andrews. Some zones along the south- and south-west coast are more suitable for adoption are likely at lower risk from adverse impacts from NSF implementation where these do not impact downstream hydrology and water allocation, but the economics of these operations following the methods proposed by Andrews remains undetermined.

7. Designing a Monitoring Protocol to Assess the Effectiveness and Impacts of NSF

The review of published literature and interviews identify the very limited direct evidence and empirical data on the successes or failures of NSF, to inform the applicability, efficacy and risks in SWWA. A key theme that emerged from interviews, particularly with the NSF community, was the desire to gather additional data that allows for an assessment of NSF that moves beyond desktop review. A key component of this review was to consider priorities for monitoring and what a monitoring or validation project may look like.

Best Practice in Monitoring/Evaluation

A key limitation of (very limited number of current) case studies is the lack of a control or pre-intervention data, and this is highlighted in relation to a scientific review of NSF practices in NSW (e.g. ARC Linkage work of Bush et al and the CSIRO expert review panel).

Any monitoring program must address this issue, which is fundamental to collecting the data required to answer the question of the impacts, benefits and issues of NSF, relative to some kind of control. Best practice is that any Monitoring and Evaluation (M/E) study, would be:

- Based on a NSF intervention catchment/area that is benchmarked against an identical/comparable, second “paired” catchment/area for a period of time prior to the intervention, followed by monitoring of both catchments over a period of time which is informed by the processes of interest and the expected timeframes of adjustment/change (preferred experimental model), or
- Based on a long-term data baseline (longer baseline would be required than above scenario) within one catchment/area, that is then subject to NSF interventions and monitored over a sufficiently long period of time.

A key aspect of a thorough M/E program to assess the impact and effectiveness of NSF is consideration of the key processes that NSF is seeking to influence, and then using this to inform the time for system adjustment and response. This needs to be incorporated as guidance for the M/E program. The points highlighted by NSF proponents should also be considered – namely, that any assessment should be executed in a holistic way consistent with NSF’s key objectives, and should consider on-farm and off-farm internal and external factors (i.e. not limited to a hydrological and financial farming systems assessment of NSF against a conventional farming operation).

As a guide, the types of processes that NSF seeks to influence includes land degradation processes, soil carbon and soil health/fertility, agricultural productivity, and riparian condition, but also off-farm factors such as nutrient and chemical impacts. These processes are likely to respond to land management changes such as NSF over a period of at least 5-10 years, however, may take decades to respond. Another key aspect to consider is that NSF seeks to influence both typical conditions but to also make the landscape more resilient to extreme events. As such, the timeframes for a M/E program should consider the time of adjustment/response but also capture important climatological variation events such as high magnitude rainfall (floods and surface flow erosion events) and drought. Many of the landscape factors that NSF seeks to influence change and respond over periods of decades rather than seasons/years or individual events, and any M/E program needs to be designed with this context.

Monitoring and Evaluating NSF

Any monitoring protocol to examine the effectiveness of NSF will require an investigation into baseline groundwater, surface water, soil conditions, plus vegetation including pasture, riparian and other trees and crops. All of these factors will need to be monitored at a frequency that represents the variability of these factors, which may be at the scale of events and weeks to months, whereas others will have a seasonal (wet/dry) to intra- and inter-annual variability. This variability will then help build a context to develop a robust time-series to address the question of NSF intervention effectiveness and efficacy. This M/E program then needs to run across a suitable duration to evaluate the effectiveness of NSF interventions. The scope of monitoring will also depend on the extent of NSF intervention on individual properties.

This review has identified hydrological and hydrogeological impacts of NSF and identified questions around the viability of NSF as a farming system in relation to claims about soil fertility and productivity from NSF. Interviewees also questioned the role of factors such as residual or legacy nutrient resources (especially phosphorous) within the soils related to past synthetic fertiliser additions that are not part of NSF farming practices, but yield may be impacted by run-down of nutrients under a low-input farming system such as NSF. Any assessment of crop yield needs to consider this issue of residual fertiliser store when generating realistic data that reflects the NSF farming system yield, productivity and profit.

Another important factor established in Chapter 6, was that the landscape setting within which NSF occurs is not consistent through SWWA. It found that risks/opportunities from landscape rehydration are variable from high gradient and rainfall coastal catchments to older, flatter inland catchments. Findings from a M/E program need to be considered in this landscape context, as results in one hydrozone may not represent the effectiveness and efficacy of NSF as a farming method in a different hydrozone.

With an individual site, the techniques already used by organisations such as DPIRD for surface and groundwater investigations, land degradation processes assessment, soil health and quality assessment, and farming systems productivity and profitability may be used as a starting point for guiding the scope of a M/E program. This should then use a best practice approach using paired sites and with due consideration of the hydrozone context. That is, replicating the approach across an appropriate number of representative hydrozone sites.

As part of the monitoring program, properties downstream of NSF properties should also be included in baseline monitoring and at the conclusion of monitoring. This was one the major concerns raised by the Southern Cross University ARC Project, and the CSIRO expert panel – that downstream properties could be negatively affected by upstream landowners ponding water on their properties and diminishing downstream flow and sediment transport.

Areas of interest for monitoring purposes include:

- Groundwater level and quality (especially salinity) underlying the site, including a drilling and monitoring design that tests the groundwater density stratification of fresh/salt water proposed by NSF. Methods used by DPIRD to conduct farm-scale hydrogeological and ground investigation studies as bisecting cross-sections are suggested as an appropriate starting point for the conceptual design of a NSF groundwater monitoring program that would be implemented within the NSF intervention catchment and a neighbouring paired catchment. This should also consider the proposed density stratification mechanisms from NSF and ensure nested bores allow for the testing of this hypothesis of freshwater sitting atop the aquifer.

- Surface water:
  - Hillslope surface runoff and soil moisture status
  - Ponding on the ground surface, including hillslopes and valley floor
  - In-stream flow quantity (quickflow/baseflow proportions), water quality (turbidity, nutrients), and in-channel velocity
- Monitoring patterns of river geomorphology and river type (planform), sediment dynamics including sediment bars and bank erosion, the effectiveness of stepped leaky weir structures, and sediment deposition/erosion on floodplains.
- Monitoring of groundwater salinity and soil salt accumulation and surface salt scald extent.
- Soil health and fertility on the floodplain and hillslopes, including testing of the same hillslope/catena locations between the NSF and non-NSF sites, and comparing the different components within NSF systems that are subjected to various interventions including encouraging vegetation growth, mulching and redistribution of harvested materials.
- Ecological and farming fodder productivity surveys of pasture/vegetation to monitor crop/production and pasture cover, health, productivity, and biomass.

Table 11 presents a summary of proposed groundwater, surface water, sediment, vegetation and soil analyses/investigations as well as nominated investigation criteria using appropriate ANZECC or Western Australian water quality standards or trigger values as a reference, as well as a statistical comparison between the intervention and paired control catchments.

Table 11: Attributes to consider for a NSF monitoring and evaluation paired catchment trial

Medium	Activity	Equipment/Laboratory Analysis	Frequency	Hypothesis or question being tested
Meteorology	Measure key meteorological parameters that are the descriptors of water and energy inputs and balance that drive rainfall, evaporation and transpiration	Standard DPIRD telemetered meteorological station	Sub-hourly	Basis for establishing landscape rehydration and water balance from NSF
Groundwater	Groundwater bore installation – targeting the surficial and underlying aquifer, preferably in a nested vertical structure to investigate any groundwater density stratification Measurement of groundwater bore levels (loggers) to continuously monitor EC, pH and water level, groundwater sampling and analysis, including the collection of in-situ field parameters (pH, EC, temperature)	Major anions and cations Water quality indicators (pH, EC) Nitrate and phosphorus Farming system chemical (herbicide/insecticide/fungicide) residue	Intervention and paired control sites instrumented for 3 years pre-intervention Continuous logging and monitoring/logger servicing biannually in September-November (groundwater high) and February-March-April (groundwater low) Continue for 5-10 years after intervention	Test enhanced aquifer recharge Test for density stratification mechanism from fresh aquifer recharge
Surface Water	Install flow gauging structures (broad crested with inset v-notch weir), surface water data loggers (EC, temperature, water level) up and down-stream of nominated leaky weirs Surface water sampling at nominated sampling points Macroinvertebrate sampling	Major anions and cations Water quality indicators (pH, EC, TDS) Nitrate and phosphorus Sediment load Farming system chemical (herbicide/insecticide/fungicide) residue Macroinvertebrate community dynamics (SIGNAL or similar), plus stream temperature	Intervention and paired control sites instrumented for 3 years pre-intervention. Continuous logging and monitoring/logger with bi/tri-annual water quality and macroinvertebrate sampling during high (July/August) and low (September/October) flows, cease-to-flow sampling of river pools at end of dry-season (March-April). Continue for 5-10 years after intervention.	NSF retain more water in the landscape for longer Impacts of NSF on water quality and aquatic diversity

Vegetation (including riparian)	Establish surface and canopy monitoring locations, bi-annual monitoring of vegetation cover Establish vegetation monitoring plots for bi-annual assessment (dry/wet seasons)	% Canopy cover and Leaf Area metrics (e.g. LiCOR or similar) Ground cover assessment of species and pasture cuts for biomass. Pasture assessment at plots across a catena from hillslope to riparian areas, assessing biomass, nutritive value, species diversity/dominance, palatability forage quality.	Monitor for 3 years pre-intervention and 5-10 years post-intervention Biannual monitoring in winter/summer	NSF increases pasture biomass Test for pasture diversity, quality and nutritive value
Soil (floodplain, hillslope)	Soil moisture monitoring of landscape rehydration Soil nutrients and nutrient cycling Soil physical and chemical properties	Annually at same time (end of dry season): • Total Organic Carbon (TOC) • Salt content (EC 1:5) • Soil test (cations/anions/nutrients) • Soil survey including surface grain size analysis / distribution (once-off) Drone/total station/Terrestrial Laser Scanning survey of river geomorphology (annually to every 2 years, or after events)	Monitor annually for 3 years pre-intervention and 5-10 years post-intervention Once-off soil survey	NSF increases soil moisture Establish mechanisms of NSF nutrient cycling and soil fertility Measure availability and any run-down of key nutrients under NSF
Productivity and Profitability	Monitor grazing pressure and head count, plus crop yield as the basis for conducting a full farming system evaluation	Collate data for each season across the trial to make a full assessment of farming system input costs and output profits	Monitor annually for the 3-year pre-intervention period and 5-10 years of M/E trial	Test profitability of NSF as a farming system
Off-site Impacts and Externalities	Consider off-site factors that NSF seeks to address and assess the effectiveness of	Major anions and cations; Nitrate and phosphorus Sediment load	Bi/tri-annually water quality sediment sampling.	Establish indirect and external impacts and factors of NSF

	NSF in addressing these and compare NSF to conventional practices: • Nutrient export • Chemical export • Sediment export	Farming system chemical (herbicide/insecticide/fungicide) residue	Start 3 years prior to intervention and continue for 5-10 years after intervention	relative to a reference farming system

8. Conclusion

This review has considered available evidence from published material and interviews to assess the applicability, efficacy and risks of Natural Sequence Farming in the dryland agricultural zone of south west Western Australia.

What is NSF?

NSF is based on principles and work in the Hunter region of New South Wales, by Peter Andrews OAM. The aim of NSF is to intervene in landscapes to rehydrate and increase water availability on hillslopes and recharge the alluvial aquifer, and reduce channel incision and soil erosion, while promoting soil fertility and productivity. The review identifies that there are three main components of NSF: 1) manipulate the hydrology, 2) increase soil fertility, and 3) create a plant succession pathway including through the use of weeds and fast-growing species. These components/objectives of NSF are summarised as follows:

- Landscape rehydration by stepped diffusion via hillslope structures to retain water in the landscape for longer,
- Recreating a specific river morphology using leaky weirs allowing water to cascade between steps (created by weirs), and
- Maximising vegetation cover, including by promoting weed growth.

This review finds that defining what NSF is and what it exactly involves is challenging. From the interviews, some respondents identified that NSF should be practised as recorded by Peter Andrews and directly aligned to the training through NSF organisations such as TALS and Tarwyn Park Training. Others stated that their version of NSF was informed by starting with these writings, information and/or training, and then adapting the methods accordingly. NSF practitioners differed in their views for using weeds and various types of vegetation. Some suggested that NSF methods should consider the local context and use native species such as *Casuarina* and *Melaleuca* rather than willow and poplar. Contrastingly, others strongly advocated for rigorously adhering to Andrews' guidelines, contending that NSF outcomes can only be achieved through methods such as using willows and blackberries. Weeds were cited by many in the NSF community as the primary pioneer pathway for vegetation succession and that trees such as Eucalypts are poorly suited to the Australian landscape and should be replaced by species such as poplar, which are less fire-prone and provide valuable leaf mulch.

The review identified areas where confusion, misunderstandings, disconnection, and contradiction of terms have arisen in NSF literature, and the conventional and academic understanding of these terms and principles. For example:

- NSF literature extensively refers to "chain of ponds" river morphology, but the river they describe is not this specific geomorphic type.
- No published data or expert opinion outside of the NSF community was found that supports the proposed mechanism of freshwater recharge of alluvial aquifers that creates a freshwater lens by density stratification and assists in addressing salinity. While this phenomenon is observed in a glass of water and on sand-islands, there is no evidence for this within southwestern Australia. All available published literature and expert opinion align with the expert scientific review on NSF methods in the Hunter

region, which is that the mechanism proposed by NSF in saline groundwater systems will likely result in elevated water tables and accelerate land degradation from salinity.

- The term “natural” in relation to NSF practices is also highlighted as not consistent with accepted academic definitions, as the promotion of non-native species and use of weeds directly aligns to the definition of a “novel” (rather than natural) ecosystem.

Risks and Opportunities

In assessing the applicability, efficacy and risks of NSF in SWWA, some clear benefits from this land management method were identified. As identified by the ARC report on work in NSW, any method that reduces grazing pressure and maximises land cover will have a beneficial effect on soil erosion processes, including wind erosion and raindrop impacts. Expert interviews also identified that the promotion of mulch farming had been shown to yield some benefits in relation to controlling surface evaporation and surface evapo-concentration of salts at the surface of the soil that can cause salinity. However, the focus of NSF on promoting surface water ponding and recharge would likely override any benefits from salt suppression via evaporation control through mulching.

There was no evidence to support the hypothesis proposed by NSF proponents that there is density stratification of fresh groundwater, overlying saline water within aquifer systems of the WA grainbelt. This was succinctly summarised by one interviewed hydrogeologist, who suggested that this hypothesis has already been extensively tested – namely, vegetation clearance in the south west agricultural region and a century of enhanced freshwater recharge has not culminated in tens of meters of freshwater overlying saline groundwater across the SWWA grainbelt. All published work and expert opinion on surface and groundwater salinity concluded that any methods that cause enhanced recharge or surface water ponding lead to surface salinity in SWWA. NSF methods, therefore, present a real and significant risk from land degradation from salinity in catchments with (particularly shallow) saline groundwater systems. This area represents the main grain production areas of SWWA.

A key foundation of NSF is the promotion of declared weed species, including willow and blackberry as a pathway to vegetation succession to boost soil fertility and improve ground cover. Work in NSW suggests that native river oak (*Casuarina cunninghamiana*) can be as effective and work in south western Australia identifies the role of Sheoak (*Allocasuarina*) and paperbark (*Melaleuca*) as a geomorphically effective colonising species. Consulted NSF practitioners in WA stated that they did not use or advocate for the use of declared pest species listed on the Western Australian Organism List (WAOL) as part of NSF interventions.

There was an absence of any published or written guidelines for earthworks design as part of NSF interventions. A common theme that emerged from interviews across the agriculture, consultant geomorphology/hydrology and NSF practitioner communities was the lack of training and skills in earthworks planning, design and construction. Prior training in this area, previously delivered by State Departments of Agriculture through training and extension programs that have not occurred in the last 20 years, was identified as a major barrier, combined with the costs in seeking professional hydraulics design services. Failure of earthworks structures was seen as a key risk to the “social licence” to undertake NSF for both practitioners and farmers undertaking these interventions, particularly where there is the potential to impact downstream properties.

A further barrier to NSF interventions in relation to earthworks was identified in that broadacre farming has moved away from surface water engineering structures and earthmoving. This has included limited new construction of structures, but also the removal of legacy surface water management infrastructure. This has been driven by equipment automation and GPS controlled traffic that has focused on achieving increased efficiency. The drying climate in SWWA has also meant that there is less intense rainfall during winter and surface water runoff issues have decreased. A key factor identified by farming systems experts were the high costs associated with lost production as a result of the construction of contour banks, in addition to costs arising from the earthworks.

A key limitation and question on the viability of NSF as a (particularly broadacre cropping) agricultural farming systems is both the areas of property lost to production from structures and the 1/3 rule proposed by Peter Andrews. Andrews proposed that the interventions in the landscape will boost productivity by around ten times and this allows for production on only 1/3 of the land. NSF proposes that the other 2/3 of the land on hillslopes and riparian areas are removed from production such as grain growing. No published literature could be found that supports the increase in productivity from NSF interventions, and no farming systems experts thought that the scale of productivity increases suggested by Andrews are viable in the climate and soils of southwestern Australia. Interviewees familiar with the NSF principles stated that these claims related to the ideals that NSF creates a stepped diffusion broadacre hydroponics land management system that allows the soils to be close to field capacity and provides the mechanism for such an increase in productivity. This is the basis for needing only 1/3 of the land to provide for a profitable farming operation.

Based on the interviews, there is limited support within the conventional agriculture community to suggest that NSF is a viable farming system for broadacre cropping systems. The ability to run a profitable farming enterprise when using only 1/3 of the land area for cropping or grazing is not consistent with the approach that growers have used to remain locally and globally competitive in seeking to farm large areas very efficiently. Where profit and efficiency are not the main objectives of farming, NSF may offer an option for people who have other objectives, but care needs to be taken in some (particularly dry, flat and salt-prone) landscapes.

The NSF community identified that convention farming systems do not necessarily include the external and indirect costs (such as off-site chemical impacts or high-nutrient runoff) that may degrade other systems and argued that any holistic assessment of NSF should consider all internal and external factors in assessing viability, cost and impact of any farming system.

Applicability and efficacy of Natural Sequence Farming

For most of the landscape hydrological zones (hydrozones) within southwestern Australia considered in this review, NSF methods are generally considered to be beneficial for (that is to reduce the risk of) land degradation from wind erosion, soil compaction and soil organic carbon, and to a lesser extent soil acidity. Based on available evidence and interviews, NSF is considered to exacerbate current risks across most hydrological zones of SWWA in relation to salinity. The impact on water erosion was assessed as dependent on the scale and quality of structures constructed as part of interventions.

Based on:

- Work in NSW, including the CSIRO expert panel and recommendations in the ARC Linkage Report in New South Wales,

- Case studies and interviews with NSF proponents and experts in hydrology, geomorphology, farming systems and hydrogeology,

It is suggested that NSF is most suitable or least likely to cause adverse land degradation issues in the following landscapes:

- The rejuvenated and steeply sloped catchments near the Darling Scarp of the Avon Basin (e.g. Toodyay, Northam, York areas).
- Areas of the Chapman Valley (Sugarloaf System).
- The higher rainfall and hydrologically connected catchments draining to the coast from Perth to Esperance (the south west and south coastal areas of WA).
- Limited areas of sandplain systems in the Swan Coastal Plain and Perth Basin with no salinity risk.
- Applied with caution in sandplain systems in the medium rainfall zone with no present surface salinity issues (e.g. Meckering & Wongan Hills area), and on skeletal soils in rejuvenated systems where rainfall is above around 350 mm areas, and some similar land systems along the south coast.

These areas can be summarised as the higher rainfall (>600 mm) zone, and with caution in higher gradient and more connected and rejuvenated landscapes of SWWA with low salinity risk (thin regolith and sandplain systems) in moderate rainfall (>400 mm) zones. These are the well-drained landscapes that contain localised and fresh groundwater systems that have a low risk to the development of secondary salinity.

Examples of NSF or NSF-like farming operations were most commonly associated with smaller-scale primary production, including equestrian and livestock production, often supported by off-farm income or other financial support or subsidy. While the most suitable areas are those with lower salinity risks, these catchments are also under more pressure around surface water allocations and flood risk, and where in-stream interventions may impact downstream properties.

Widespread implementation of NSF principles across the broadacre cropping and mixed grazing-cropping farming systems of the grainbelt of SWWA is considered unlikely. The main reason for this is that the NSF philosophy places restrictions on the production area, which then constrains the financial viability of broadacre, particularly cropping farming systems. In addition to this, the flow retention structures are likely to interfere with efficient cropping operations. Based on all available evidence, NSF interventions across the grainbelt would cause significant land degradation issues from waterlogging and salinity.

At present, there is no published data or peer-reviewed literature on the applicability, efficacy and risks of Natural Sequence Farming within the dryland agricultural zone of south west Western Australia. Based on this review and interviews with knowledge-holders, it was concluded that for the majority of landscapes within SWWA and agricultural enterprises, NSF is unlikely to be adopted for financial, practical and environmental risk reasons. Landscapes in higher rainfall areas that do not have a salinity risk and are favourable for more niche or lifestyle farming opportunities, NSF offers a farming and land management philosophy that people may choose to adopt.

References

Abbe, T., & Brooks, A. (2011). Geomorphic, engineering, and ecological considerations when using wood in river restoration. *Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools* (pp. 419-451): American Geophysical Union Washington, DC

Andrews, P. (2006). *Back from the Brink: How Australia's Landscape Can Be Saved*. Sydney NSW: ABC Books

Andrews, P., Goldney, D., Mitchell, D., & Newell, P. (2005). Natural Sequence Farming. In H.L. Davies (Ed.), *the 20th annual conference of the Grasslands Society of NSW* (pp. 44-45). Orange, NSW: Grassland Society of NSW

Andrews, P., & Hodda, N. (2008). *Beyond the brink*. WF Howes Limited

Barrett-Lennard, E.G., George, R.J., Hamilton, G., Norman, H.C., & Masters, D.G. (2005). Multi-disciplinary approaches suggest profitable and sustainable farming systems for valley floors at risk of salinity. *Australian Journal of Experimental Agriculture, 45*, 1415-1424

Blake, A. (2009). A Short Review of Natural Sequence Farming and its Applicability in Western Australia. In. Unpublished: Department of Agriculture and Food, Western Australia

Bradshaw, C.J.A. (2012). Little left to lose: deforestation and forest degradation in Australia since European colonization. *Journal of Plant Ecology, 5*, 109-120

Brierley, G.J., Cohen, T., Fryirs, K., & Brooks, A. (1999). Post-European changes to the fluvial geomorphology of Bega catchment, Australia: implications for river ecology. *Freshwater Biology, 41*, 839-848

Bush, R. (2010). ARC Project Report (LP4455080): Restoring hydrological connectivity of surface waters and groundwaters: biogeochemical processes and environmental benefits for river landscapes. In. Lismore, NSW: Southern Cross University

Callow, J.N., Hipsey, M.R., & Vogwill, R.I. (2020). Surface water as a cause of land degradation from dryland salinity. *Hydrology and Earth System Sciences, 24*, 717-734

Cartwright, I., Weaver, T.R., Simmons, C.T., Fifield, L.K., Lawrence, C.R., Chisari, R., & Varley, S. (2010). Physical hydrogeology and environmental isotopes to constrain the age, origins, and stability of a low-salinity groundwater lens formed by periodic river recharge: Murray Basin, Australia. *Journal of Hydrology, 380*, 203-221

Charles, M.D. (1960). The Challenge of Landscape: The Development and Practice of Keyline [Review of The Challenge of Landscape: The Development and Practice of Keyline]. *Geographical Review, 50*, 463-464

Charlton, R. (2007). *Fundamentals of fluvial geomorphology*. Routledge

Cheetham, M.D., Bush, R.T., Keene, A.F., Erskine, W.D., Fallon, S., & Jacobsen, G. (2010). Resolving the Holocene alluvial record in southeastern Australia using luminescence and radiocarbon techniques. *Journal of Quaternary Science, 25*, 1160-1168

Collier, M.J., & Devitt, C. (2016). Novel ecosystems: Challenges and opportunities for the Anthropocene. *The Anthropocene Review, 3*, 231-242

Conacher, A.J., Combes, P.L., Smith, P.A., & McLellan, R.C. (1983a). Evaluation of throughflow interceptors for controlling secondary soil and water salinity in dryland agricultural areas of southwestern Australia: I. Questionnaire surveys. *Applied geography (Sevenoaks), 3*, 29-44

Conacher, A.J., Neville, S.D., & King, P.D. (1983b). Evaluation of throughflow interceptors for controlling secondary soil and water salinity in dryland agricultural areas of southwestern Australia : II. Hydrological study. *Applied geography (Sevenoaks), 3*, 115-132

Coram, J. (1998). National Classification of Catchments for land and river salinity control. In. Barton ACT: Rural Industries Research & Development Corporation

DeBano, L.F., & Schmidt, L.J. (1989). General Technical Report RM-182: Improving southwestern riparian areas through watershed management. In U.S.D.o. Agriculture (Ed.). Fort Collins, Colorado: USDA Forest Service

Department of Agriculture and Food (2013). Report card on sustainable natural resource use in agriculture. In. Western Australia: Department of Agriculture and Food

Department of Primary Industries and Regional Development (2019). Annual Report 2019. In D.o.P.I.a.R. Development (Ed.). Perth, Western Australia: Department of Primary Industries and Regional Development

Department of Primary Industries and Regional Development (2020). Salinity tolerance of plants for agriculture and revegetation. In: Department of Primary Industries and Regional Development,

Diamond, J. (2004). *Collapse: How societies choose to fail or succeed*. Viking Press

Dobes, L., Weber, N., Bennett, J., & Ogilvy, S. (2013). Stream-bed and flood-plain rehabilitation at Mulloon Creek, Australia: a financial and economic perspective. *The Rangeland Journal, 35*, 339-348

Doody, T.M., Nagler, P.L., Glenn, E.P., Moore, G.W., Morino, K., Hultine, K.R., & Benyon, R.G. (2011). Potential for water salvage by removal of non-native woody vegetation from dryland river systems. *Hydrological Processes, 25*, 4117-4131

Erskine, W.D., Chalmers, A.C., Keene, A.F., Cheetham, M.D., & Bush, R.T. (2009a). Role of a rheophyte in bench development on a sand-bed river in southeast Australia. *Earth Surface Processes and Landforms, 34*, 941-953

Erskine, W.D., Keene, A.F., Bush, R.T., & Cheetham, M.D. (2009b). Biogeomorphic processes of channel contraction since the 1960s on the sand-bedded, Widden Brook, Australia. In, *7th International Conference on Geomorphology (ANZIAG). Ancient Landscapes - Modern Perspectives* (pp. 6-11). Melbourne Australia: Australia and New Zealand International Association of Geomorphologists

Eyles, R.J. (1977). Birchams Creek: the transition from a chain of ponds to a gully. *Australian Geographical Studies, 15*, 146-157

Fertilizer Industry Federation of Australia (2006). *Australian Soil Fertility Manual*. (3rd ed. ed.). Collingwood: CSIRO Publishing

Fryirs, K., & Brierley, G. (2013). *Geomorphic Analysis of River Systems An Approach to Reading the Landscape*. (1st ed. ed.). Somerset: Wiley

George, R., & Bennett, D. (2004). Impact of Farm Forestry Systems on Dryland Salinity: A Modelling Case Study. In, *Australian Forestry Conference*. Melbourne VIC

Greenwood, H., O'Dowd, D.J., & Lake, P.S. (2004). Willow (Salix× rubens) invasion of the riparian zone in south-eastern Australia: reduced abundance and altered composition of terrestrial arthropods. *Diversity and Distributions, 10*, 485-492

Hatton, T., & Nulsen, R. (1999). Towards achieving functional ecosystem mimicry with respect to water cycling in southern Australian agriculture. *Agroforestry Systems, 45*, 203-214

Hatton, T., Ruprecht, J., & George, R. (2003). Preclearing hydrology of the Western Australia wheatbelt: target for the future. *Plant and soil, 257*, 341-356

Henschke, C., & Bessell-Browne, J. (1983). An assessment of WISALTS banks at Dangin

Henschke, C.J. (1989). Review of the WISALTS bank installations. In. Perth, Western Australia: Department of Agriculture and Food

Hickson, O. (2017). Surface water and alluvial groundwater connectivity at Mulloon Creek and the implications for Natural Sequence Farming. In, *School of Earth and Environmental Science*: The University of Wollongong

Hobbs, R.J., Higgs, E., & Harris, J.A. (2009). Novel ecosystems: implications for conservation and restoration. *Trends in ecology & evolution (Amsterdam), 24*, 599-605

Hobbs, R.J., & McIntyre, S. (2005). Categorizing Australian landscapes as an aid to assessing the generality of landscape management guidelines. *Global Ecology and Biogeography, 14*, 1-15

Holt, T., Greskowiak, J., Seibert, S.L., & Massmann, G. (2019). Modeling the Evolution of a Freshwater Lens under Highly Dynamic Conditions on a Currently Developing Barrier Island. *Geofluids, 2019*, 1-15

Hurditch, W. (2015). Sustainable water and energy management in Australia's farming landscapes. *WIT Transactions on Ecology and the Environment, 200*, 329-341

Jacobsen, T., & Adams, R.M. (1958). Salt and silt in ancient Mesopotamian agriculture. *Science, 128*, 1251-1258

Johnston, P., & Brierley, G. (2006). Late Quaternary river evolution of floodplain pockets along Mulloon Creek, New South Wales, Australia. *The Holocene, 16*, 661-674

Jones, J.J.B. (2012). *Plant Nutrition and Soil Fertility Manual*. (2nd ed. ed.). Boca Raton: CRC Press

Keene, A., Bush, R., & Erskine, W. (2007). Connectivity of stream water and alluvial groundwater around restoration works in an incised sand-bed stream. In, *the Fifth Australian Stream Management Conference: Australian Rivers: Making a Difference'. Albury, NSW* (pp. 21-25)

Keene, A.F., Bush, R.T., Cheetham, M.D., Chalmers, A.C., & Erskine, W.D. (2008). Pool-riffle reformation and bed armouring induced by structures and riparian revegetation that sequester sand. In J. Schmidt, T. Cochrane, C. Phillips, S. Elliot, T. Davies, & L. Basher (Eds.), *Sediment dynamics in changing*

environments (pp. 576-583). Wallingford: IAHS Publication

Knighton, A.D., & Nanson, G.C. (2000). Waterhole form and process in the anastomosing channel system of Cooper Creek, Australia. *Geomorphology, 35*, 101-117

Mactaggart, B., Bauer, J., & Goldney, D. (2007). When History May Lead us Astray: using historical documents to reconstruct swampy meadows/chains of ponds in the New South Wales Central Tablelands, Australia. *Australian Geographer, 38*, 233-252

Massy, C. (2017). *Call of the Reed Warbler : A New Agriculture – A New Earth*. Chicago, United States: University of Queensland Press

McCown, R., Freebairn, D., & Hammer, G. (1992). A framework for research on improved management of agricultural production systems. In K. Hutchinson, & P. Vickery (Eds.), *Proceedings of the 6th Australian Agronomy Conference* (pp. 214-217). Armidal, New South Wales: Australian Society of Agronomy Inc.

McFarlane, D., Engel, R., Ryder, A., & Eales, M. (1990). Level banks used to decrease waterlogging can increase salinity. *Journal of the Department of Agriculture, Western Australia, Series 4, 31*, 74-77

McFarlane, D., George, R., & Caccetta, P. (2004). The extent and potential area of salt-affected land in Western Australia estimated using remote sensing and digital terrain models. In S. Dogramaci, & A. Waterhouse (Eds.), *Engineering Salinity Solutions : 1st National Salinity Engineering Conference 2004*. Barton, A.C.T: Engineers Australia

McFarlane, D., George, R., Ruprecht, J., Charles, S., & Hodgson, G. (2020). Runoff and groundwater responses to climate change in South West Australia. *Journal of the Royal Society of Western Australia, 103*, 9-27

Monkhouse, F. (1960). The Challenge of Landscape: The Development and Practice of Keyline [Review of the Challenge of Landscape: The Development and Practice of Keyline]. *The Geographical Society, 126*, 99-100

Morse, N.B., Pellissier, P.A., Cianciola, E.N., Brereton, R.L., Sullivan, M.M., Shonka, N.K., Wheeler, T.B., & McDowell, W.H. (2014). Novel ecosystems in the Anthropocene: a revision of the novel ecosystem concept for pragmatic applications. *Ecology and society, 19*, 12

Mould, S., & Fryirs, K. (2017). The Holocene evolution and geomorphology of a chain of ponds, southeast Australia: Establishing a physical template for river management. *Catena, 149*, 349-362

Natural Sequence Farming: Frequently Asked Questions. In

Newell, P., & Reynolds, G. (2005). NSF - Principles & Applications. In

Norris, D., & Andrews, P. (2010). Re-coupling the carbon and water cycles by Natural Sequence Farming. *International journal of Water, 5*, 386-395

O'Bree, R., & Andrews, P. (2017). 'Yanget farm' rehydration project by Rod O'Bree and Peter Andrews. In. TALS Institute

Peel, M.C., Finlayson, B.L., & McMahon, T.A. (2007). Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences, 11*, 1633-1644

Pettit, N., & Froend, R.H. (1992). *Research into reforestation techniques for saline groundwater control*. Water Authority of Western Australia

Pope, L., Finlayson, B., & Rutherfurd, I. (2007). Are waterways with willows wider? In, *5th Australian Stream Management Conference. Australian rivers: making a difference, Charles Sturt University, Thurgoona, New South Wales* (pp. 324-329)

Prosser, I.P., Chappell, J., & Gillespie, R. (1994). Holocene valley aggradation and gully erosion in headwater catchments, south-eastern highlands of Australia. *Earth Surface Processes and Landforms, 19*, 465-480

Raper, G., Speed, R., Simons, J., Killen, A., Blake, A., Ryder, A., Smith, R., Stainer, G., & Bourke, L. (2014). Groundwater trend analysis for south-west Western Australia 2007–12. In. Western Australia, Perth: Department of Agriculture and Food

Read, M., & Barmuta, L. (1999). Comparisons of benthic communities adjacent to riparian native eucalypt and introduced willow vegetation. *Freshwater Biology, 42*, 359-374

Robertson, M. (2005). *Stop bushland weeds: a guide to successful weeding in Aouth Australia's bushland*. (2nd ed.). Nature Conservation Society of South Australia

Rogers, G., & Bauer, B. (2006). Preliminary Investigation of effects of Natural Sequence Farming (NSF) on soil organic matter levels and nutrient uptake at Baramul. In P. Hazell, & D. Norris (Eds.), *The First Natural Sequence Farming Workshop: Natural Sequence Farming–Defining the Science and the Practice*. Bungendore, NSW

Rutherford, I. (2018). Why is everyone talking about natural sequence farming? In M. Ketchel (Ed.): The Conversation

Ryan, J.G., McAlpine, C.A., Ludwig, J.A., & Callow, J.N. (2015). Modelling the potential of integrated vegetation bands (IVB) to retain stormwater runoff on steep hillslopes of Southeast Queensland, Australia. *Land, 4*, 711-736

Scott, A. (2001). Water erosion in the Murray-Darling Basin: Learning from the past

Smakhtin, V.U. (2001). Low flow hydrology: a review. *Journal of hydrology (Amsterdam), 240*, 147-186

Somerville, P., White, I., Macdonald, B., Bush, R., & Jasonsmith, J. (2009). Surface and groundwater connectivity and salinity in the upper Hunter Valley. In, *IAH Symposium on Groundwater in the Sydney Basin*. Sydney Australia: International Association of Hydrogeologists,

Tane, H. (2006). Restoring watershed systems by converting to natural sequence farming. In, *Proceedings of the First Natural Sequence Farming Workshop, Natural Sequence Farming-Defining the Science and the Practice. Bungendore, NSW, Australia, SRCMA*

Truitt, A.M., Granek, E.F., Duveneck, M.J., Goldsmith, K.A., Jordan, M.P., & Yazzie, K.C. (2015). What is Novel About Novel Ecosystems: Managing Change in an Ever-Changing World. *Environmental management (New York), 55*, 1217-1226

Wasson, R.J., Mazari, R.K., Starr, B., & Clifton, G. (1998). The recent history of erosion and sedimentation on the Southern Tablelands of southeastern Australia: sediment flux dominated by channel incision. *Geomorphology, 24*, 291-308

Weaving, S.J. (1999). Native Vegetation Handbook for the Shire of Toodyay. In Department of Agriculture and Food (Ed.). Perth

Weber, N., & Field, J. (2010). The influence of Natural Sequence Farming stream rehabilitation on upper catchment floodplain soil properties, Hunter Valley, NSW, Australia. In, *19th World Congress of Soil Science, Soil Solutions for a Changing World*

Werner, A.D., & Laattoe, T. (2016). Terrestrial freshwater lenses in stable riverine settings: Occurrence and controlling factors. *Water resources research, 52*, 3654-3662

Wiley, T. (2017). Catchment Function Analysis using Google Earth Mapping*, 20*

Wiley, T., & O'Bree, R. (2020). Landscape Rehydration & Regenerative Agriculture - whole farm demonstration on Jack Wood's farm at Toodyay. In: Tierra Australia Pty Ltd

Williams, J. (2010). The principles of Natural Sequence Farming. *International journal of Water, 5*, 396-400

Williams, R.T., & Fryirs, K.A. (2020). The morphology and geomorphic evolution of a large chain-of-ponds river system. *Earth Surface Processes and Landforms, 45*, 1732-1748

Wohl, E., Bledsoe, B.P., Jacobson, R.B., Poff, N.L., Rathburn, S.L., Walters, D.M., & Wilcox, A.C. (2015a). The Natural Sediment Regime in Rivers: Broadening the Foundation for Ecosystem Management. *Bioscience, 65*, 358-371

Wohl, E., Lane, S.N., & Wilcox, A.C. (2015b). The science and practice of river restoration. *Water resources research, 51*, 5974-5997

Yeomans, P.A. (1954). *The keyline plan*. Sydney: Waite & BUll

Young, W., Evans, R., Olley, J.M., Milham, N., Robertson, A., & Smith, C.J. (2002). The 'Natural Farming Sequence'. In. Canberra: CSIRO

Zierholz, C., Prosser, I., Fogarty, P., & Rustomji, P. (2001). In-stream wetlands and their significance for channel filling and the catchment sediment budget, Jugiong Creek, New South Wales. *Geomorphology, 38*, 221-235

Appendix 1: Interview Questions

The following is a list of indicative questions used as part of the semi-structured interviews. Questions were removed/added depending on the specific knowledge/expertise of the person being interviewed.

Section 1: NSF Methods

- Can you describe what specific interventions NSF involves?
- Can you describe what the interventions NSF uses to control hillslope hydrological processes, and how contour banks are used, placed and designed for landscape rehydration?
- Can you describe what is involved with leaky weirs and the efforts manage river flows and retain water in the river?
- What are the key processes that drive recharge of the alluvial aquifer through leaky weirs built as part of NSF?
- Can you discuss what you think NSF seeks to achieve in creating the chain of ponds morphology in a river and how applicable this is to locations within southwestern Australia?
- Can you describe how the leaky weirs, aquifer recharge and separation of the dense salt and less-dense fresh water discussed as part of NSF works and can you give some specific examples of this in your own work or where you have seen this working?
- Can you describe the effectiveness of weeds that have been used in landscape revegetation as part of NSF?
- Have you seen positive or adverse impacts from the use of weeds as part of revegetation strategies in NSF interventions or other interventions and land management?
- Can you discuss the evidence you have seen for the impact of NSF on soil fertility? What are the processes involved?
- Where within southwestern Australia have you seen NSF applied, or some NSF methods implemented? Describe how this had positive or detrimental outcomes and the specific evidence.

Section 2: Efficiency and Effectiveness of NSF

- What in your opinion, which of the methods used by NSF to achieve landscape rehydration are more or least successful?
- How are contour banks designed and placed in the landscape, specifically, how are they different to keylines?
- How effective are leaky weirs and what sites have you seen them used?
- Do leaky weirs recharge the alluvial aquifer and what evidence have you seen of this?

- Have you seen evidence of salinity being increased or decreased (managed) through the use of leaky weirs or grade control structures (rock dumps), and where was this and what were the characteristics?
- What evidence have you seen that weeds more effective than native species for revegetating landscapes?
- Where within southwestern Australia is NSF most suitable to be implemented?
- Can you describe the different hydrological and landscape zones within southwestern Australia, and summarise the evidence you have that NSF would be effective or ineffective in those locations?

Section 3: Risks, Issues, Success and Monitoring of NSF

- Have you seen failure and erosion caused by failed contour banks as part of NSF?
- Have you seen evidence for the benefits or adverse impacts of leaky weirs or grade control structures in river systems?
- Describe the different types of hydrological and landscape zones within southwestern Australia and the risks from salinity that interventions from NSF may cause.
- Which specific hydrological and landscape zones within southwestern Australia would the interventions of NSF most likely work, and what key processes would be changed and how?
- Which specific hydrological and landscape zones within southwestern Australia would the interventions of NSF most likely cause hard or land degradation, and what key processes would be changed and how?
- What are the key parameters that should be monitored to assess the success of NSF at the farm scale?
- What are the key parameters that should be monitored to assess issues and land degradation from NSF at the farm scale?
- What are the key parameters that should be monitored to assess the success of NSF at the catchment scale?
- What are the key parameters that should be monitored to assess issues and land degradation from NSF at the catchment scale?