

## Phase farming with trees: An option for dryland salinity control and feedstock for bioenergy

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### 1. ABSTRACT

The integration of woody perennials into farming systems is advocated as a way of remediating many environmental problems such as salinity, erosion and loss of biodiversity. Permanently placed trees in low rainfall areas are often uneconomic due to crop displacement, reductions in crop yield, low value products or lack of markets for products. Phase farming with trees (PFT) has been proposed as an option for salinity control in the 300-600 mm rainfall zone of southern Australia, where it is estimated that 17 Mha of farmland is under the threat of salinity. PFT is designed to grow trees at high planting densities in ultra-short rotations (4-5 years) to de-water soil and reduce recharge while also improving soil structure and producing woody biomass for “green power” generation.

The fundamental premise of the system is that trees can rapidly de-water soil profiles to several metres depth and thus create a buffer of dry soil, with this being refilled during the subsequent agricultural phase. A survey of soil water extraction by existing plantings of common farm forestry species was undertaken to give an indication of the potential rooting depths and rates of root growth of these species. Soil cores were taken beneath oil mallees (*Eucalyptus* spp.), *E. astringens*, *Acacia acuminata* and *Allocasuarina huegeliana*, aged 4-11 years, at 15 sites representative of the major soils across south-west Western Australia. In several cases trees had dried subsoils to depths greater than 10 m. To determine if the rate of water depletion could be accelerated by species selection and silvicultural management, and thus the length of the tree rotation shortened, we established an experiment on a typical farm in the Western Australian wheatbelt. *Eucalyptus globulus*, *E. occidentalis*, *Acacia celastrifolia*, *Pinus radiata* and *Allocasuarina huegeliana* were planted at four densities 500, 1000, 2000 and 4000 stem ha<sup>-1</sup>. Soil water content beneath *E. occidentalis* planted at 4000 stem ha<sup>-1</sup> has been depleted to 4 m after only 20 months growth.

The scale of the salinity problem will require land treatments that can be rapidly deployed across millions of hectares of farmland. Phase farming with trees appears to be a promising development for de-watering soil profiles, reducing recharge to groundwater and lessening the risk of salinisation in agricultural landscapes. A market is required for the resultant biomass – much of the area that must be treated is distant from ports and processing facilities for traditional wood products. Bioenergy production, using small and dispersed generation capacity may thus not only reduce carbon emissions from fossil fuels but also help overcome another major natural resource management problem. The technical and economic issues for broad scale adoption of this radically new farming system, such as costs and methods of establishment, harvesting and stump removal are obvious impediments to adoption and are discussed in this paper.

## 2. INTRODUCTION

The replacement of native vegetation with agricultural systems has resulted in rising watertables and expanding areas of dryland salinity across southern Australia. Current estimates predict over 17 Mha will be affected by 2050 (National Land and Water Resources Audit, 2001). In Western Australia alone the area of farmland currently affected by secondary salinity is estimated to be 1.8 Mha, and it is predicted that a further 7 Mha will become saline. Annual crops are shallow-rooted and only transpire water for part of the year. As a consequence, recharge under agricultural systems is one to two orders of magnitude greater than under native vegetation (Allison *et al.*, 1990; Tennant and Hall, 2001), resulting in rising watertables and mobilisation of salt stored within the regolith.

Incorporation of deep-rooted perennial species into catchments dominated by annual crops and pastures forms part of the strategy for managing dryland salinity in southern Australia (Stirzaker *et al.*, 2002) and such revegetation may also remediate other environmental problems such as erosion and loss of biodiversity through habitat removal. However, permanently placed trees in low rainfall areas can often be uneconomic due to crop displacement, reductions in crop yield due to competition for water, low value products or a lack of markets for products. Similarly, several studies have suggested that trees only have a local effect and will need to be planted over as much as 80% of the landscape to reduce salinity (George *et al.*, 1999).

In low (300-600 mm) rainfall areas, 'phase farming with trees' (PFT) comprising ultra-short rotations (3-5 years) of tree crops has been proposed as an option to reduce recharge via the creation of a buffer for the leakage from subsequent annual crop rotations (Harper *et al.*, 2000). As the aim is to remove water as quickly as possible from the greatest possible soil volume, a number of techniques that would sensibly be avoided in normal low rainfall forestry have been suggested. These include high planting densities, the use of fertilisers to promote growth and the use of faster growing species from higher rainfall areas. The PFT system, based on short tree rotations including a subsequent fallow period (~ five years) followed by extended cropping periods (~ 15 years), would eliminate the potential for crop yield reductions that occur in agroforestry systems with closely spaced permanent tree belts (Knight *et al.*, 2002; Stirzaker *et al.*, 2002).

Ultra-short rotation tree plantations have been used for biomass production in higher rainfall areas (Joslin and Schoenholtz, 1997; Thornton *et al.*, 1998), or the maintenance of soil fertility in developing countries (Boye *et al.*, 2002). However, the use of fast-growing perennial tree species to deplete stored soil water in low rainfall areas is untested. PFT is broadly analogous to the inclusion of perennial pastures such as lucerne (*Medicago sativa*) in cropping rotations for increasing water-use and reducing recharge (Crawford and MacFarlane, 1995; Ward *et al.*, 2001). Although lucerne uses comparatively more water than annual crops and pastures as it is deeper rooting, and has an extended period of water uptake (Ward *et al.*, 2001), it is intolerant of acidic, waterlogged or saline soils as well as intensive grazing (Humphries and Auricht, 2001). This, therefore, restricts the use of lucerne to selected areas. Trees are suited to a broader range of soil conditions and also have the potential to be deeper rooting than lucerne.

Simulations of PFT were undertaken using the WAVES model (Zhang and Dawes, 1998) for a number of sites in both Western Australia (Merredin, mean rainfall 320 mm, potential evaporation 1800 mm) and the Murray Darling Basin (Walpeup, Victoria-340 mm, 1750 mm

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and Hillston, NSW-581 mm, 1750 mm) (Harper *et al.*, 2000). This modelling was based on the assumption that the rooting depth of *Eucalyptus globulus* was at least 10 m within three to five years of establishment. Several scenarios were examined, and these suggested broad differences in the likely response to the PFT system.

1. 20 m deep sandy soils. Here PFT depleted soil water storage and stopped the recharge under agriculture ( $100 \text{ mm yr}^{-1}$ ) within 2-3 years of planting. The high recharge rates resumed three years into the next agricultural phase. PFT was deemed unsuitable for such soils with the best strategy being permanent blocks of trees.
2. Soils with 1 m of sand overlying 2 m of clay, with and without a fresh water table and with a saline water table. Here recharge rates returned to a maximum within 1-5 years of clearing the trees. It is likely that soil salinity will accumulate under the trees grown over a saline water-table, with this requiring leaching before another rotation is possible. Permanent plantations of salt tolerant perennials are recommended in these situations.
3. Soils with a clayey surface horizon. Here the rates of recharge were very low ( $1 \text{ mm yr}^{-1}$ ) under agriculture and trees may only be required at very long rotation intervals ( $\sim$  decades).
4. Soils with 1 m of sand overlying 9 m of clay. Here PFT depleted soil water storage and stopped recharge within two years of planting and leaf area index equilibrated with rainfall after five years. It was predicted that recharge would not commence under the subsequent agricultural systems for 15 years. These results suggest the possibility of a crop-tree rotation of five years of trees followed by 15-20 years of crops or pasture.

The sites where the technique appears to be most applicable require soil profiles extending to several metres depth, without any root inhibiting layers such as hardpans or watertables. In Western Australia such materials occur under the ubiquitous deeply weathered laterite soils (McArthur, 1991), although the extent of such profiles in eastern Australia is less clear.

Apart from the presence of deep soil profiles, another assumption of the PFT system is that tree roots can reach this depth within three to five years. While there are many observations of tree roots at depth (Stone and Kalisz, 1991; Canadell *et al.*, 1996) these are often for older trees and the physical and chemical constraints to tree root growth and rate of soil exploration by roots are not well defined. Two-year-old mallee eucalypts planted on deep sands at  $5000 \text{ stems ha}^{-1}$ , extracted water from at least five meters depth (Eastham *et al.* 1994). Similarly, three-year-old *Eucalyptus grandis* planted on deep rhodic ferralsols (clay loam-sandy loam), in South Africa, were found to extract water to a depth of at least eight meters (Dye, 1996).

To better understand the depth and speed of subsoil root exploration we undertook studies to (a) determine if the basic premise of the system, that is rapid de-watering of soil profiles to several metres depth, was valid and (b) whether the depth of soil water depletion and in effect, the tree rotation length, could be manipulated by species selection or silvicultural inputs. The field experimental sites also form the basis of an extension programme and will allow practical difficulties such as stump removal to be resolved. The temporal integration of trees into agriculture also poses a series of issues that need to be addressed, including economics, and in particular the cost of establishment, potential markets and valuing the land conservation benefits of reducing recharge, and the practicality of removing the tree stumps at the end of the tree rotation. We discuss these issues and offer some potential solutions.

## 3. METHODS

### 3.1 Rooting depth of farm forestry species

Rooting depths and soil water extraction of a range of common farm forestry species including oil mallees (*Eucalyptus* spp.), *Eucalyptus astringens*, *Acacia acuminata* and *Allocasuarina huegeliana* were investigated at 15 sites representative of the major soils of the < 600 mm rainfall zone of south-west Western Australia. Soil cores were taken to depths of up to 12 m directly underneath trees and in adjacent paddocks of annual crops or pasture. Cores with a diameter of 50 mm were sampled at 50 cm depth intervals, using a hollow auger wireline retrieval system.

Soil water matric potential (Greacen *et al.*, 1987) and gravimetric water content were determined from soil cores. Soil physical and chemical properties including, particle size analysis, total soil chloride content, pH and electrical conductivity (1:5), were determined at 50 cm depth intervals. Dry bulk densities were taken from backhoe pits and were estimated from sections of the soil core where possible. The depth of rooting was estimated by changes in soil water content and soil water matric potential with depth. The maximum extent of rooting was taken to be the depth where soil matric potential was similar to pre-dawn leaf potential measured with a pressure chamber (Scholander *et al.*, 1965) at the time of soil sampling.

### 3.2 Phase farming with trees trial

*3.2.1 Site description.* The PFT trial site is located at Valema Farms (32.38°S, 117.78°E), near Corrigin, Western Australia, approximately 200 km east of Perth. This site is typical of the sandy surfaced soils of the Western Australia wheatbelt. The climate is Mediterranean with long term annual average rainfall (90 years) and pan evaporation (12 years) of 375 and 1823 mm yr<sup>-1</sup>, respectively. The annual rainfall in 2001, the year of establishment was 321 mm and in 2002 it was 261 mm.

The trial design consists of three replicate blocks each with 25 treatments comprising five species; *Eucalyptus globulus*, *Eucalyptus occidentalis*, *Acacia celastrifolia*, *Allocasuarina huegeliana* and *Pinus radiata* planted at 500, 1000, 2000 and 4000 stems ha<sup>-1</sup>, as well as 500 stems ha<sup>-1</sup> plus fertiliser. The three blocks are situated in the same paddock, and arrayed across different landscape positions. Block 1 is on a gravelly ridge, Block 2 in a midslope concavity with a sandy duplex profile and Block 3 with a sandy duplex profile with a moderately saline watertable at 2-3 m. All soils have formed on deep weathering profiles in excess of 10 m deep, this being assessed prior to trial establishment. Tree seedlings were planted in August 2001 onto land that had been cropped the previous year. The site was ripped to 50 cm and herbicide sprayed for weed control.

*3.2.2 Plant Biomass.* Plant survival and biomass including height, diameter and leaf area index have been measured annually. At age four years (2005), trees will be harvested and dry weight biomass measured. Various techniques will be assessed to determine the practicality of removing the stumps and returning the site to productive agriculture.

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3.2.3 *Soil Water Content*. Soil water contents to 8 m are measured at monthly intervals using a neutron moisture meter for each species planted at densities of 1000 and 4000 stem ha<sup>-1</sup> and *E. globulus* for all densities. Soil water contents to 8 m are also measured in a blank plot in each replicate block and to 3 m in the adjacent paddock.

### 4. RESULTS

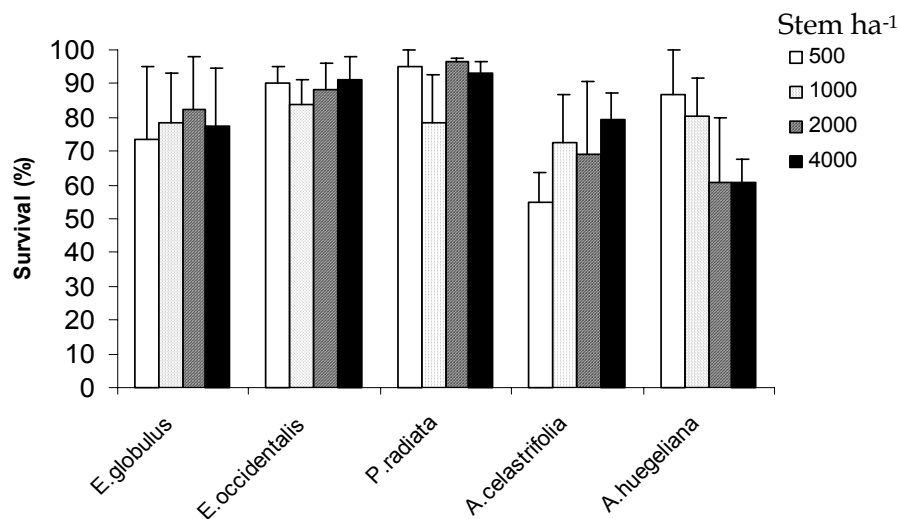
#### 4.1 Rooting depth of farm forestry species

Soil water extraction profiles beneath trees were compared with soil bulk density, texture, pH and salinity. The rooting depths for existing plantings are shown in Table 1. Mallee eucalypt roots were found to penetrate and dry to wilting point massive clayey subsoils with bulk densities as high as 1.8-2.0 g cm<sup>-3</sup> to depths of 8-10 m within seven years of planting. Similarly, roots had penetrated subsoils with pH values ranging from 4.2 to 6.6 and electrical conductivity (EC<sub>1:5</sub>) values up to 125 mS m<sup>-1</sup>. At sites where the rooting depth was less than the maximum drilling depth, the limit to rooting was not correlated with any change in soil physical or chemical properties. More detailed results of soil properties and rooting depth for mallee eucalypts are present in Robinson *et al.* (2002).

**Table 1. Site characteristics and rooting depth of various farm forestry species estimated from changes in soil matric potentials and soil water contents with depth as well as comparison with values measured in adjacent pasture**

Species	Age (yr)	Planting density (stem ha <sup>-1</sup> )	Soil texture	Depth of dry soil (m)	Maximum extent of drilling (m)
<i>Eucalyptus astringens</i>	4	1100	clay	4	7
<i>E. astringens</i>	4	2500	clay	3.5	6
<i>Allocasuarina huegeliana</i>	11	833	sandy clay loam	6.5	7.5
<i>Acacia acuminata</i>	11	833	clay	3	8
<i>E. loxophleba</i> subsp <i>loxophleba</i>	11	833	clay	6.5	12
Oil Mallee Eucalypts					
<i>E. horistes</i>	7	5000, 2-row hedge	sandy clay loam	10	10
<i>E. kochii</i> subsp <i>plenissima</i>	5	5000, 2-row hedge	sandy clay loam	9	11
<i>E. kochii</i> subsp <i>plenissima</i>	7	5000, 2-row hedge	clay loam	7.5	10
<i>E. kochii</i> subsp <i>plenissima</i>	9	2500	sandy loam	8.5	8.5

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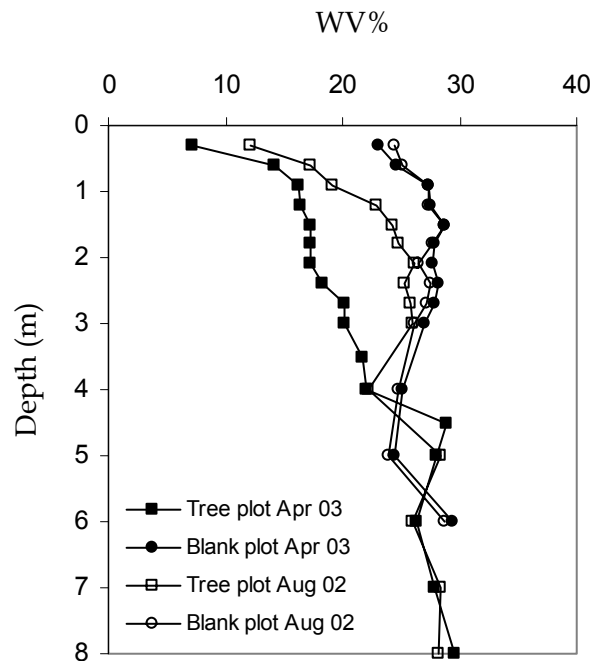
**Figure 1. Survival of species planted at 500, 1000, 2000 and 4000 stem ha<sup>-1</sup> one year after planting for the Corrigin phase farming with trees trial**

Soil water extraction profiles beneath eleven-year-old plantings on a soil with a high clay content (34-54%) indicated differences in the ability of different species to explore the subsoil and extract water. Soil water extraction beneath *Acacia acuminata* was to 3 m depth in comparison to *Allocasuarina huegeliana* and *Eucalyptus loxophleba* subsp. *loxophleba*, where soil was dried to wilting point to 6.5 m. The estimated rooting depth of four-year-old *Eucalyptus astringens* was only 4 m.

### 4.2 Phase farming trial

**4.2.1 Survival and growth.** Average survival rates ranged from 61 to 96% after the first year (Figure 1). Survival was strongly affected by site with no significant effect of planting density. Although the replicates were situated in the same paddock, Block 1 on the gravelly upper slope had much lower survival for all species compared with Block 2 and 3. Tree height and leaf area measurements taken in August 2002 indicate that *E. globulus* and *E. occidentalis* had the greatest growth in the first year.

**4.2.2 Soil moisture content.** An effect of the trees on soil water content was apparent in some of the high density plots after only 20 months growth. Examples of the soil water profiles beneath the trees and blank plots are shown in Figure 2. The soil moisture profiles under the blank plot were similar in August 2002 and April 2003. In contrast there had been depletion of soil water beneath a high density *E. occidentalis* plot to a depth of 4 m in April 2003 (Figure 2).



**Figure 2. Soil water profiles under *E. occidentalis* 4000 stem ha<sup>-1</sup> and blank plots measured at the end of winter August 2002 (□,○) and the end of summer April 2003 (■,●)**

## 5. DISCUSSION

### 5.1 Depth of rooting

Our measurements suggest that there were no identifiable soil limits to tree root growth, despite extreme values of soil bulk density. In some instances hardpans within the soil prevented drilling, and it is uncertain whether the roots had penetrated these layers. The depth of mallee eucalypt roots at seven years of age provides the best evidence that tree roots are able to occupy the soil profile in a relatively short amount of time. The mallee eucalypt plantings investigated were mainly planted as belts rather than blocks, therefore deeper rooting may be expected when trees are planted at higher density such as found by Eastham and Rose (1990) and this has been demonstrated in early results from the Corrigin field experiment.

In contrast to the majority of mallee plantings, the rooting depth of *E. astringens* was only 3.5 to 4 m after four years. The plantation that we assessed was situated on a moderate slope, with a perched water table present in winter and this indicates the influence of site characteristics on the rate of soil water depletion. *Allocasuarina huegeliana* and *Eucalyptus loxophleba* had greater rooting depths than *Acacia acuminata* at the same site.

### 5.2 Phase farming with trees experiment

Initial growth measurements indicate that the two *Eucalyptus* species, and *E. occidentalis* in particular, had high survival rates and the most rapid growth across all plots. Soil water measurements beneath *E. occidentalis* indicate the potential for rapid

soil water depletion under high density plantings. Results almost half way through the tree rotation indicate that *E. occidentalis* has the most potential for PFT. This species naturally occurs adjacent to salt lakes and therefore has the capacity to tolerate saline sub-soil conditions, and may therefore be suitable for planting over broad areas. With the large genetic diversity within native eucalypts it is possible that other species are better still, moreover there may be interactions between genotypes and sites, with some species performing better in specific environments compared to others. Although comparisons over a greater number of sites and of more species need to be undertaken, these results suggest that there are prospects of considerable improvement in the rate of water depletion through species selection.

### 5.3 Paddock scale application of PFT

Large areas of Australian farmland and water supplies are at risk from salinization and the scale of the salinity problem will require land treatments that can be rapidly deployed across millions of hectares of farmland. We suggest that PFT may provide a new approach that will deplete stored soil water, create a dry buffer and reduce recharge to groundwater systems. It similarly has the potential to produce large amounts of biomass across the region. There are, however, a number of issues to be resolved for PFT to be feasible at a paddock and farm scale. These include:

*5.3.1 Cost of establishment.* Although the high density treatment at 4000 stem ha<sup>-1</sup> is the most favourable in terms of rate of soil water depletion, using seedlings would cost approximately \$1000 ha<sup>-1</sup> for the seedlings alone. Added to this are the substantial costs of planting and site preparation. This is clearly untenable, on land valued at \$400-500 ha<sup>-1</sup>. The cost of establishment could be dramatically reduced by direct seeding using existing farm equipment. Although direct seeding has often been used for revegetation establishment rates are lower than in a controlled environments with reported ranges for *Acacias* and *Eucalypts* of, 10-40% and 2-20%, respectively (Dalton, 1993). Further development is required to increase the reliability of this establishment method before large scale application.

*5.3.2 Identifying a product.* Widespread adoption of PFT will produce large amounts of biomass from small trees. Potential products for existing markets include short rotation pulp and wood fibre for reconstituted wood products such as paper and fibre-board. The productivity of four year old trees in the < 600 mm yr<sup>-1</sup> rainfall zone will be low. In a survey of *E. globulus* plantings across south-western Australia (Harper *et al.*, 1999), 16 plots in five plantations with rainfall < 600 mm yr<sup>-1</sup> had growth data at four years of age. These plots had total bole volumes that ranged between 7 to 26 m<sup>3</sup> ha<sup>-1</sup>, and estimated biomass production of 5 to 18 t ha<sup>-1</sup> at four years.

Low productivity together with the large distances to product markets currently makes most potential products uneconomic. The most likely markets for the PFT material are (a) biomass for power generation and (b) restoring catchment water balances and reducing the risk of salinity. In recent years there has been increasing interest in development of sustainable and renewable energy sources (Bartle and Shea, 2002), with a pilot biomass energy plant currently being built by Western Power in Narrogin. Although there has been much discussion about valuing environmental services and the introduction of salinity credits, these markets are yet to be developed. Nonetheless, it is essential that the likely environmental benefits of PFT are valued in some form.

## 5.4 From trees to crops

At the end of the tree rotation large areas of high density tree plantation will need to be converted back to a state suitable for annual cropping, and low cost methods of removing or working around stumps left after harvest need to be developed. The tree harvesting options will depend on the product. Biomass harvesters that reduce either the whole plant or stems into chips on-site may be cheaper than standard tree harvesting techniques. Machinery currently under development for harvesting of oil mallee eucalypts would be suitable, however for biomass production it may also be possible to harvest the upper portions of the stumps. The other option is to leave the stumps and crop around them. Four and five-year-old sycamore (*Plantus occidentalis*) biomass crops have been successfully harvested and converted to a no-till corn system in Tennessee (Devine *et al.*, 2002). After harvest stumps were treated with glyphosate to prevent sprouting. No mechanical problems were encountered when planting no-till corn over stumps in the first season following the woody biomass crop, and there was substantial decay of stumps in the second season and third season. For the first two years following conversion from sycamore there was an increased nitrogen fertiliser requirement for optimal corn yields. A similar option for PFT may be to follow the tree crop rotation with one or two years of pasture, this allowing some rotting of the stump and other debris.

## 6. CONCLUSIONS

Initial results from the PFT trial are promising with significant soil water depletion beneath high density planting in a relatively short amount of time. Continued success of the trial in the remaining two years will encourage landowners to consider broader scale application of the system. Problems such as harvesting and stump removal associated with the practical application of the system may be overcome by adapting methods used in other agroforestry systems. Nonetheless, they require serious consideration if the system is to be considered a normal part of farm practice across large areas of land. Similarly, considerable development is required of the bioenergy aspects of the concept, including a whole life cycle analysis.

## 7. ACKNOWLEDGMENTS

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