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Herbicide Tolerance Options for Weed Control in Lanza® Tedera

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Abstract: Tedera is a drought-tolerant perennial forage legume introduced in Australia in 2006. In October 2018, T15-1218 Lanza®, the world's first tedera variety, was released by the Department of Primary Industries and Regional Development and Meat & Livestock Australia for commercial use. A key agronomic practise for the successful establishment and adoption of tedera is to have a robust herbicide package to control a range of grass and broadleaf weeds well tolerated by tedera. A total of 9 pre-emergent and 44 post-emergent herbicide treatments were evaluated in eight experiments from 2017 to 2021. To control grasses such as annual ryegrass (*Lolium rigidum* Gaud.), propyzamide and carbetamide can be recommended for pre- or post-emergent applications and butroxydim, clethodim, and haloxyfop for post-emergent applications. The broadleaf pre-emergent herbicides recommended are clopyralid to control emerged capeweed (*Arctotheca calendula* (L.) Levyns), fomesafen to control pre-emergent wild radish (*Raphanus raphanistrum* L.), and the double mix of fomesafen + diuron, flumetsulam + diuron, and the triple mix of fomesafen + diuron + flumetsulam to control pre-emergent capeweed, pre- and post-emergent wild radish, and other broadleaf weeds. The most consistently well tolerated post-emergent herbicides by tedera seedlings and adult plants were diflufenican, diuron, flumetsulam, fomesafen, and their two- or three-way mixes that will provide good control of capeweed and wild radish. Desiccants such as paraquat or diquat were also well tolerated by 1-year-old tedera plants that recovered after being desiccated.

Keywords: *Bituminaria bituminosa*; propyzamide; flumetsulam; fomesafen; diflufenican; diuron; clethodim; butroxydim; haloxyfop

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1. Introduction

Tedera (*Bituminaria bituminosa* var. *albomarginata*) is a drought-tolerant perennial forage legume native to the Canary Islands where it was traditionally utilized for direct grazing and/or cut-and-carry to produce high value goat cheese [1–3]. Tedera became a priority species for domestication and breeding leading to commercial release as a consequence of promising results of multi-species evaluation conducted across southern Australia in programs conducted by the Plant-Based Solutions for Dryland Salinity Cooperative Research Centre (Salinity CRC) and the Future Farm Industries Cooperative Research Centre (FFI CRC) [4–8]. The model of an integrated dryland agricultural system (MIDAS) widely used in Australia to assess farm-level evaluations of crops/forages and management innovations ([9]) was utilized to evaluate the impact of tedera at a farm level. MIDAS modelling results indicated that tedera offered the potential to increase farm profit by up to 26% [10]. Tedera breeding was conducted by the Department of Primary Industries and Regional Development of Western Australia (DPIRD) and in October 2018, the first cultivar, T15-1218 Lanza® was released by DPIRD and Meat & Livestock Australia (MLA) for commercial use in Australia.

During domestication and breeding of tedera, parallel research programs developed strategies for agronomic management and animal production. The animal production research concluded that: (a) grazing tedera did not cause any ill-effect to the grazing animals even when grazed either as a sole diet or in mixtures at different times of the year [11–13] and (b) tedera proved to be a valuable summer and autumn feed for sheep in Mediterranean-type climates [14]. The agronomy information was required for a newly domesticated species to cover all aspects of production [15], utilisation and seed harvesting under the prevailing local conditions.

Weed control is essential for the successful establishment of forage species [16–19]. Identification of herbicides that can reduce the competition of grass and broadleaf weeds without significantly affecting tedera production was a high priority requirement. The slow growth of tedera as a seedling makes it a poor initial competitor against weeds, especially broadleaf weeds. Moreover, tedera crops grown for seed production need to be weed free for high seed yield and quality. Use of herbicides is the primary strategy for weed control in the broadacre farming systems of Western Australia. Since tedera is novel to managed agriculture, there are no herbicides yet registered for use on this species.

Investigations on tolerance of tedera to herbicides initially focussed on herbicides registered on other legumes for effective weed control. Kelly [20] reported that five weeks after application of flumetsulam at 20 g a.i./ha and diflufenican at 75 g a.i./ha to one-month old tedera (accession PNF23-A15) had no significant negative effect on shoot dry weight of tedera compared to the un-sprayed control. Tedera seedlings were most susceptible to MCPA at 375 g a.i./ha, and diflufenican 12.5 g + MCPA 125 g a.i./ha and had intermediate susceptibility to bromoxynil 300 g a.i./ha. Mature tedera plants exhibited few initial symptoms of damage from flumetsulam and diflufenican. However, six weeks after spraying, they were not significantly different from the un-sprayed control. MCPA, diflufenican + MCPA and glyphosate were all reported to cause major damage.

Gray [21] reported on the survivorship and biomass four weeks after spraying tedera seedlings at third trifoliate leaf stage (accessions T2, T42, T48 and T51). Herbicides tested were flumetsulam at 16 g a.i./ha, diflufenican at 50 g a.i./ha, bromoxynil at 56 g a.i./ha, imazamox at 24.5 g a.i./ha, atrazine at 900 g a.i./ha and oxyfluorfen at 86.4 g a.i./ha and two non-selective herbicides (glyphosate at 540 g a.i./ha and glufosinate at 200 g a.i./ha). Results identified that flumetsulam, imazamox, diflufenican, and oxyfluorfen had no effect on tedera seedling survival and flumetsulam, imazamox, and diflufenican resulted in the lowest reductions in plant biomass of 13.9%, 19.5% and 29.9%, respectively. Atrazine resulted in no surviving seedlings (100% kill), while bromoxynil delivered 80% seedling survival and oxyfluorfen and bromoxynil treatments caused significant biomass reductions of 72% and 79%, respectively. As expected, the non-selective herbicides glyphosate and glufosinate greatly reduced tedera seedling survival to 35% and 0%, respectively [21].

Gray [21] reported the tolerance of one-month-old tedera seedlings (accession T48) to five application rates (control, half of label recommended rate (½RR), RR, double RR (2RR) and quadruple RR (4RR) of four selective herbicides (label recommended rates were flumetsulam at 16 g a.i./ha, diflufenican at 50 g a.i./ha, imazamox at 24.5 g a.i./ha and imazethapyr at 70 g a.i./ha) and one non-selective herbicide (glyphosate at 540 g a.i./ha). Four weeks after treatment, seedling survival was unaffected in comparison with the un-sprayed control ($p > 0.05$) for flumetsulam, diflufenican, and imazethapyr with all application rates. Flumetsulam caused the least plant biomass reduction of tedera seedlings and only 20% and 30% biomass reduction were recorded at 2RR and 4RR application rates, respectively. Diflufenican reduced plant biomass by between 25% at RR and 40% at 4RR. Tedera seedlings were very sensitive to imazethapyr; at ½RR, it reduced biomass by 30%. For imazamox, 4RR reduced survival to 70% while glyphosate at ½RR resulted in 30% plant survival. Imazamox and glyphosate were also quite detrimental in biomass production; at ½RR, there was a 55% and 70% biomass reduction, respectively.

Moore [22] reported the results of a field experiment where 12 herbicides were applied in spring at Barrule farm, near Kojonup, Western Australia (37.9 S, 117.3 E). A logarithmic sprayer was utilised to determine the dose response of a 3-month-old tedera stand (accessions T4, T27, T31, T42, T43, T48, and T52), which was 10–15 cm tall with 10–25 leaves. Tedera tolerance to the range of herbicides and doses were evaluated four weeks after spraying. Tedera tolerated with less than 10% visual damage the maximum rates applied of flumetsulam at 160 g a.i./ha, imazamox at 140 g a.i./ha, and imazethapyr at 350 g a.i./ha. Diflufenican at 250 g a.i./ha, bromoxynil at 400 g a.i./ha plus MCPA at 400 g a.i./ha, and bromoxynil at 500 g a.i./ha plus diflufenican at 50 g a.i./ha mix (maximum applied rates) were also tolerated with less than 50% damage to tedera. A mix of amitrole (50 to 500 g a.i./ha) + paraquat (25 to 250 g a.i./ha), terbutryn (50 to 500 g a.i./ha), and glyphosate (90 to 900 g a.i./ha) produced a range of responses by tedera over the range of rates tested. Atrazine (90 to 900 a.i./ha), cyanazine (180 to 1800 g a.i./ha) and metribuzin (75 to 750 g a.i./ha) were damaging to tedera at normal label rates.

List of herbicides evaluated in tedera in 1-month-old seedlings or in plants older than 3 months prior to 2017 reported above are presented in Table 1.

Table 1. List of herbicides evaluated in 1-month-old tedera seedlings or in tedera older than three months prior to 2017.

1-Month-Old	Older than 3 Months
atrazine	amitrole + paraquat
bromoxynil	atrazine
diflufenican	bromoxynil + diflufenican
flumetsulam	cyanazine
glufosinate	diflufenican
glyphosate	flumetsulam
imazamox	glyphosate
imazethapyr	imazamox
MCPA	imazethapyr
MCPA + diflufenican	MCPA
oxyfluorfen	MCPA + bromoxynil
	MCPA + diflufenican
	metribuzin
	terbutryn

This paper reports on the herbicide tolerance of tedera, which has been generated in experiments from 2017 to 2021, with the objective of identifying pre- and post-emergent herbicides to control grasses and broadleaf weeds without causing significant damage to tedera. We hypothesized that evaluation would reveal that: (1) tedera would tolerate at least one pre-emergent and one post-emergent herbicide used for the control of grasses such as annual ryegrass (*Lolium rigidum* Gaud.); and (2) tedera would tolerate at least one pre-emergent and one post-emergent herbicide used to control the most common broadleaf weeds in southern Australia such as capeweed (*Arctotheca calendula* (L.) Levyns) and wild radish (*Raphanus raphanistrum* L.). Annual ryegrass, capeweed, and wild radish are main problematic weeds in crops and pastures in Southern Australia [23].

2. Materials and Methods

Eight herbicide tolerance experiments under fairly weed free conditions were conducted from 2017 to 2021. General experimental details are presented in Table 2 and specific details for each experiment are presented in Sections 2.1–2.8. The post-emergent herbicides were applied on actively growing plants, not stressed by prolonged periods of extreme temperatures, moisture, diseases, and/or with poor nutrition.

Table 2. General experiment details for eight tedera herbicide tolerance experiments.

Site	Exp. 1	Exp. 2.	Exp. 3	Exp. 4	Exp. 5	Exp. 6	Exp. 7	Exp. 8
Location		Dandaragan			Northam		Dandaragan	Northam
Year	2017	2018	2018	2020	2020	2020	2021	2021
Latitude		30°50′14″ S			31°39′16.31″ S		30°50′14″ S	31°39′16.31″ S
Longitude		115°45′44″ E			116°40′13.86″ E		115°45′44″ E	116°40′13.86″ E
Annual average rainfall (mm)		480			425		480	425
Irrigation		Rain-fed			Irrigated Rain-fed Irrigated		Rain-fed	Irrigated
Soil Type		Sandy loam			Sandy loam	Red sandy loam	Sandy loam	Sandy loam
Soil pH ($CaCl_2$)		6.8			5.8	5.8	6.8	5.8
Type of Experiment		Field			Field	Glasshouse	Field	Field

2.1. Experiment 1 (2017). Post-Emergent Herbicides on a 2-Year-Old Tedera Seed Crop

On 15 June 2017, a section of a tedera seed crop established in July 2015 was sprayed with 15 post-emergent herbicides plus an un-sprayed control (Table 3) in a randomized complete block design with plots of 3 m × 20 m and three replicates. Spraying was performed with Teejet AIXR11002 (coarse droplet size) nozzles and a boom output of 96 L/ha. The wind speed was 11 km/h, temperature of 20 °C, and a relative humidity of 54% (Figure 1).

Figure 1. Spraying a two-year-old stand of tedera with 15 post-emergent herbicide experiment at Dandaragan on 15 June 2017.

The effect of herbicides on the 2-year-old tedera was evaluated visually as biomass reduction and percentage of yellowing, chlorosis, and/or necrosis in comparison to the un-sprayed control four weeks after treatments application (WATA) on the 14 July 2017. Measurements were on a scale of 0–100% where 0% means no effect and 100% means plants were dead.

Table 3. Rates of active ingredient (a.i.) g/ha used in the eight experiments with post-emergent herbicides.

Herbicides	Group [1]	Exp. 1	Exp. 2.	Exp. 3	Exp. 4	Exp. 5	Exp. 6	Exp. 7	Exp. 8
Post-Emergent Herbicides									
2,4-DB	4							500;1000;2000	
2,4-DB + dlumetsulan	4 + 2							1000 + 20	
Aclonifen + diflufenican + pyroxasulfone	32 + 12 + 15								400 + 66 + 100
Bentazone	6	1440							
Bromoxynil	6	400					250;500;1000		
Bromoxynil + diflufenican	6 + 12	250 + 25				250 + 25;750 + 75	250 + 25;500 + 50		
Butroxydim	1	45	45	45					
Carbetamide	23						2070;4140	2070	
Clethodim	1	120							
Clopyralid	4								45
Cyanazine	5	1080							
Diflufenican	12	100	100	100		100;300	50;100;200;400	100	
Diflufenican + pyraflufen	12 + 14						100 + 8;200 + 16		
Diflufenican + flumetsulam + diuron	12 + 2+5						50 + 20 + 90;100 + 40 + 180	100 + 20 + 90;200 + 40 + 180;400 + 80 + 360	100 + 20 + 90
Diuron	5						450;900		
Flumetsulam + diuron	2 + 5		20 + 50	20 + 50	20 + 90;40 + 180	40 + 180	20 + 90;40 + 180	40 + 180	20 + 90
Flumetsulam	2	32	20	20					
Flumetsulam + diflufenican	2 + 12							20 + 100	
Flumetsulam + picolinafen	2 + 12							20 + 37.5	
Flumetsulam + diuron + picolinafen	2 + 5 + 12							20 + 90 + 37.5;40 + 180 + 75	
Flumioxazin	14						90;180		
Fluroxypyr	4						50;100		
Fomesafen	14						180;360	180;360	180;360
Fomesafen + diuron	14 + 5								240 + 90
Fomesafen + clopyralid	14 + 4								240 + 30
Glyphosate	9							450	
Haloxyfop	1		104	104					
Imazamox + imazapyr	2 + 2	24.75 + 11.25					10 + 4.5;20 + 9		12.4 + 5.6;24.8 + 11.2
Imazamox	2	35	35	35					
Imazethapyr	2	98	98	98					
Linuron	5	500							
MCPA + bromoxynil	4 + 6					250 + 250;750 + 750			
MCPA + diflufenican	4 + 12					250 + 25;750 + 75			
MCPA + bromoxynil + diflufenican	4 + 6 + 12					250 + 250 + 25;750 + 750 + 75			
MCPB + MCPA + flumetsulam	4 + 4 + 2							600 + 40 + 20;1200 + 80 + 40;2400 + 160 + 80	
Mesotrione	27						96;192		
Oxyfluorfen	14		120	120					
Picolinafen	12							37.5	
Prometryn	5		400	400					
Propyzamide	3	1000	1000	1000	1000; 2000				
Prosulfocarb + S-Metolachlor	15				2000 + 300; 4000 + 600				
Pyraflufen-ethyl	14		8	8			16;32		
Saflufenacil	14	23.8		23.8					
Saflufenacil + paraquat	14 + 22	23.8 + 375						23.8 + 375	
Terbuthylazine	5				900;1800				

[1] Herbicide mode of Action.

2.2. Experiment 2 (2018). Post-Emergent Herbicides on a 1-Month-Old Tedera Stand

The post-emergent experiment in the 2018 seed crop was sprayed on the 5 August 2018, five weeks after sowing (2–3 leaf stage tedera seedings) and compared 11 post-emergent herbicides (Table 3) in a criss-cross/strip-plot design with plots of 3 m × 5 m and three replicates. Eight broadleaf selective herbicides treatments (diflufenican, flumetsulam, flumetsulam + diuron, imazamox, imazethapyr, oxyfluorfen, prometryn and pyraflufen-ethyl) plus an un-sprayed control were applied in strips east-west, while three grass selective herbicides (butroxydim, haloxyfop and propyzamide) plus an un-sprayed control were applied in strip plots of 5 m × 3 m north-south, both randomised within each replicate. Spraying was performed using Teejet AIXR11002 (coarse droplet size) nozzles and a boom output of 96 L/ha. The wind speed at time of treatments applications was 10 km/h, temperature 19 °C, and a relative humidity 45%. The experiment was visually assessed for biomass reduction (%) in comparison to un-sprayed control, one and six WATA on 13 August 2018 and 14 September 2018, respectively.

2.3. Experiment 3 (2018). Post-Emergent Herbicides on a 1-year-Old Tedera Stand

A section of the 2017 seed crop was sprayed on the 28 June 2018 with 12 post-emergent herbicides (Table 3) in a criss-cross/strip-plot design/ with plots of 3 m × 5 m and three replicates. Nine broadleaf selective herbicides treatments (diflufenican, flumetsulam, flumetsulam + diuron, imazamox, imazethapyr, oxyfluorfen, prometryn, pyraflufen-ethyl and saflufenacil) were applied in strips east-west plus an un-sprayed control, while three grass selective herbicides (butroxydim, haloxyfop, and propyzamide) plus an un-sprayed control were applied in strip plots of 5 m × 3 m north-south at right angle to broadleaf herbicide application direction, both randomised within each replicate. Spraying was performed using Teejet AIXR11002 (coarse droplet size) nozzles and a boom output of 96 L/ha. At the time of treatments application, the wind speed was 12 km/h from the South, temperature was 20 °C, and relative was humidity of 40%. The experiment was visually assessed for biomass reduction (%) in comparison to un-sprayed control six and 11 WATA on 13 August and 14 September 2018, respectively.

2.4. Experiment 4 (2020). Pre-Emergent and Post-Emergent Herbicides on 1 Month Old Seedlings

On the 27 March 2020, an experiment was conducted under weed-free conditions using 10 kg/ha tedera seed rate, sown 2 cm deep in 22 cm row spacing with knifepoint and press-wheel seeding system in a split-plot design. The main plots had two treatments of pre-emergent and post-emergent herbicide treatments application randomised completely. The sub-plots had seven herbicide treatments (Tables 3 and 4) plus an un-sprayed control. Each experimental unit was 2 m × 3.08 m with four replicates. The pre-emergent herbicides were sprayed on the 26 March 2020, and the post-emergent herbicides were sprayed on seedlings on the 29 April 2020 using a knapsack hand-held boom-sprayer (Figure 2) fitted with Agrotop Airmix flat fan 110-01 nozzles (coarse droplet size) and calibrated to deliver 100 L/ha water. Seedling counts were taken on four 1 m rows in the middle of each 7-row plot about one month after of both pre- or post-emergent herbicide applications. Visual biomass reduction estimates were taken nine WATA on 29 May 2020. On the 25 August 2020 (21 WATA), two 50 cm × 50 cm quadrats per plot were cut to 5 cm of height per plot to assess the crop biomass.

Table 4. Rates of active ingredient (a.i.) g/ha used in experiments 4 and 8 with pre-emergent herbicides.

Herbicides	Group [1]	Exp. 4	Exp. 8
Pre-Emergent Herbicides			
Aclonifen + diflufenican + pyroxasulfone (IBS [2])	32 + 12 + 15		400 + 66 + 100
Clopyralid (PSPE [3])	4		90
Fomesafen (IBS)	14		360;720
Fomesafen (PSPE)	14		300;600
Fomesafen + diuron (IBS)	14 + 5		240 + 450
Fomesafen + diuron + Flumetsulam (IBS)	14 + 5 + 2		240 + 450 + 40
Flumetsulam + diuron (IBS)	2 + 5		40 + 450
Propyzamide (IBS)	3	1000;2000	1000
Prosulfocarb + S-Metolachlor (IBS)	15	2000 + 300;4000 + 600	
Terbuthylazine (IBS)	5	900;1800	

[1] Herbicide mode of Action, [2] IBS—Incorporated by Sowing., [3] PSPE—Post-Sowing, Pre-Emergent.

Figure 2. Spraying 1-month-old tedera seedlings with 7 post-emergent herbicides experiment at Northam on 29 April 2020.

2.5. Experiment 5 (2020). Post-Emergent Herbicides on 5-Month-Old Plants

The plots of Experiment 4 sown on the 27 March 2020 that were unaffected by the herbicide treatments were allowed to grow for 5 months, and 11 post-emergent herbicide treatments were applied using above mentioned knapsack hand-held boom sprayer (Figure 2) on the 31 August 2020 (Table 3). An un-sprayed plot per replication was included the experiment. The experiment was laid out in a randomized complete block design, and each experimental unit was 2 m × 3.08 m with four replicates. Visual assessment of the effect on flowering was assessed three WATA on 21 September 2020, and a biomass cut of a 50 cm × 50 cm quadrat/plot was taken 15 WATA on 18 December 2020.

2.6. Experiment 6 (2020). Post-Emergent Herbicides on 1 Month Old Seedlings

On the 5 October 2020, 99 4.5 L pots were filled with red sandy loam soil, sown with 12 tedera seeds each and placed in a naturally lit glasshouse set to have 20–25 °C temperature. One week after sowing, tedera rhizobium inoculant (WSM 4083) was watered into the pots. Pots were irrigated three times a week. One month after sowing, 5-leaf tedera seedings were sprayed with 31 herbicide treatments on 3 November 2020 (Table 3) using an overhead, compressed air, indoor spray-cabinet calibrated to deliver 100 L/ha at 200 kPa pressure. The 33 treatments including two un-sprayed were completely randomized in the glasshouse and replicated three times. Eight weeks after spraying, the experiment was harvested. Roots attached to the shoot were carefully washed several times manually using a water jet and a sieve (0.7 mm mesh size) to remove debris and soil particles while preventing root damage and losses. The detached roots were collected from the sieve and added to the main root mass. Root portion was separated from the shoot portion, and roots were stored in water in a cold room at 4 °C until the subsequent root image analysis, which commenced immediately afterwards. Fine cleaning of roots using forceps/tweezers was completed before scanning. All the material that was not live roots, especially dead roots which can be identified from their darker colour and lack of elasticity, was removed. Then, roots were spread into a thin layer (2–3 mm) of distilled water in a transparent plastic tray. Care was taken to fully submerge, spread roots, and minimize overlapping of roots. Roots were cut into small segments and spread with a paintbrush wherever appropriate to facilitate the above. For each sample, one or several 400 dpi resolution images were taken with a flatbed scanner (Epson Perfection V800 Photo; Epson, Nagano, Japan). When the root sample was too large to complete in one scan, the sample was divided into two or more sub-samples and images were taken for each sub-sample. The images were analysed with the software package WINRHIZO™ Pro 2007a (Regent Instruments, Quebec, QC, Canada) for total root length, average diameter, and surface area using the Global Threshold Method where a single threshold value was chosen automatically to classify all pixels of an analysed region. After scanning the roots, samples were oven dried at 60 °C for one week and root biomass assessed. The shoot length of each plant in each pot was measured. The shoots were then cut and oven dried at 60 °C for one week, and the shoot biomass was measured for each treatment.

2.7. Experiment 7 (2021). Post-Emergent Herbicides on a 3-Year-Old Tedera Stand

On the 24 June 2021, a section of a 3-year-old tedera seed crop was sprayed with 22 herbicide treatments plus three un-sprayed controls in a randomized complete block design (Table 3). Each experimental unit was 2 m × 30 m with three replicates. Visual assessments of biomass reduction (%) were conducted four and eight WATA on 22 July and 24 August 2021, respectively. A biomass cut was taken nine WATA on 31 August 2021 for each plot with a self-propelled lawnmower with a cutting width of 0.53 m and length of 5 m at a height of 5 cm. Samples were oven dried for 72 h at 60 °C, and tedera was separated from other species and weighed.

2.8. Experiment 8 (2021). Pre-Emergent and Post-Emergent Herbicides on 1-Month-Old Seedlings

On the 8 October 2021, a randomised complete block design experiment with 4 replicates was conducted with tedera sown at 2 cm deep at 10 kg/ha seed rate with 22 cm row spacing using a cone-seeder fitted with a knifepoint and press-wheel seeding system. The whole experimental area was sprayed with propyzamide 1000 a.i. g/ha to control grass weeds before application of pre-emergent treatment to the plots. The experiment had two un-sprayed controls, six pre-emergent treatments incorporated by sowing (IBS), and three post-sowing pre-emergent (PSPE) treatments applied on 8 October 2021, and 10 post-emergent treatments applied on the 11 November 2021 (Tables 3 and 4). The herbicide treatments were applied using knapsack hand-held boom-sprayer (Figure 2) fitted with Agrotop Airmix flat fan 110-01 nozzles (coarse droplet size) and calibrated to deliver 100 L/ha water. On the 14 December 2021 (9 and 4 weeks after pre- and post-emergent treatment application, respectively), using a 50 cm × 50 cm quadrat in the centre of each plot, tedera plants were counted and then cut to ground level. Samples were oven dried for 72 h at 60 °C and weighed to assess crop biomass production.

2.9. Herbicide Mode of Action

The herbicide mode of action (Group) is presented for each herbicide in Tables 3 and 4. For a full description of each herbicide, the respective commercial label in the country of interest should be read.

2.10. Statistical Analysis

Analysis of variance using Genstat was undertaken for most of the data analysis, with blocking and treatment structures appropriate for the randomized block or strip plot designs. Significance lettering was determined based on the least significant difference (l.s.d.). With experiment 2, the analysis was repeated without pyraflufen-ethyl to confirm no significant interaction without this herbicide. For experiment 4, the application of propyzamide followed by flumetsulam + diuron was considered the same treatment pre- and post-herbicide despite different rates. This was done to give a balanced strip plot design and only after checking the results supported this adjustment. With experiment 6, shoot dry weight per plant, root dry weight per plant, and total root volume per plant were square root transformed prior to analysis to give more constant variance. Results were back transformed and presented on the original scale.

3. Results

3.1. Experiment 1 (2017). Post-Emergent Herbicides on a 2-Year-Old Tedera Seed Crop

Visual phytotoxic symptoms (yellowing, chlorosis, and/or necrosis) and biomass reduction (%) of two-year old tedera caused by 15 post-emergent herbicides is presented in Table 5.

Table 5. Effect of post-emergent herbicides as visual phytotoxic symptoms (yellowing, chlorosis and/or necrosis) and biomass reduction (%) of two-year old tedera at Dandaragan.

Herbicides	Rate a.i. g/ha	Biomass Reduction (%)	Yellowing (%)	Chlorosis (%)	Necrosis (%)
		14 July 2017			
Un-sprayed control		0 a [1]	0 a	0 a	0 a
Bentazone	1440	2 a	5 ab	10 b	0 a
Cyanazine	1080	5 a	32 c	28 d	27 c
Flumetsulam	32	0 a	10 ab	0 a	0 a
Diflufenican	100	3 ab	0 a	15 bc	0 a
Bromoxynil	400	3 ab	12 ab	20 cd	15 b
Butroxydim	45	2 a	5 ab	0 a	0 a
Imazamox + imazapyr	24.75 + 11.25	0 a	60 d	0 a	0 a
Bromoxynil + diflufenican	250 + 25	3 ab	0 a	48 e	5 a
Propyzamide	1000	2 a	0 a	0 a	0 a
Linuron	500	5 ab	15 b	22 cd	12 b
Imazamox	35	2 a	10 ab	0 a	0 a
Clethodim	120	0 a	12 ab	0 a	0 a
Saflufenacil	23.8	10 b	33 c	7 ab	25 c
Saflufenacil + paraquat	23.8 + 375	58 c	0 a	0 a	58 d
Imazethapyr	98	3 ab	17 b	0 a	0 a
l.s.d. ($p = 0.05$)		7	14	9	9

[1] Figures in the columns that share a common letter are not significantly different ($p < 0.05$).

Thirteen herbicides applied, one month after spraying (14 July 2017) had no significant biomass reduction on the 2-year-old tedera plants except for saflufenacil and saflufenacil + paraquat. Flumetsulam, imazamox, butroxydim, propyzamide, and clethodim did not produce significant visual symptoms. Imazamoz + Imazapyr produced the most yellowing, bromoxynil + diflufenican produced the most chlorosis, and saflufenacil + paraquat produced the most necrosis score as expected with paraquat being a desiccant herbicide.

3.2. Experiment 2 (2018). Post-Emergent Herbicides on a 1-Month-Old Tedera Stand

There was a significant negative effect of broadleaf herbicides on tedera biomass assessed visually on 13 August 2018 and 14 September 2018 (Table 6).

Table 6. Response of 1-month-old tedera seedlings to post-emergent broadleaf herbicides applied on 5 August 2018 (5 weeks after sowing) at Dandaragan.

Herbicides	Rate a.i. g/ha	Tedera Biomass Reduction (%) 1 WATA [1] 13 August 2018	Tedera Biomass Reduction (%) 6 WATA 14 September 2018
Un-sprayed control		3 ab [2]	0 a
Flumetsulam + diuron	20 + 50	0 a	0. a
Flumetsulam	20	0 a	0 a
Diflufenican	100	10 b	0 a
Prometryn	400	3 ab	3 ab
Imazamox	35	10 b	5 ab
Imazethapyr	98	18 b	8 ab
Oxyfluorfen	120	79 c	12 b
Pyraflufen-ethyl	8	0 a	0 a
Pyraflufen-ethyl + propyzamide	8	0 a	0 a
Pyraflufen-ethyl + haloxyfop	8	83 c	60 c
Pyraflufen-ethyl + butroxydim	8	80 c	60 c
l.s.d. ($p = 0.05$)		8	10

[1] WATA = weeks after treatments application. [2] Figures in the columns that share a common letter are not significantly different ($p < 0.05$).

The broadleaf-selective herbicides that produced no biomass reduction on tedera were flumetsulam + diuron and flumetsulam, while diflufenical produced some initial biomass reduction but fully recovered by two months. Herbicides that produced minor biomass reduction but not significantly different to control were imazamox, prometryn, and imazethapyr. Oxyfluorfen caused a severe biomass reduction but had significantly recovered by five weeks after application.

There was a significant interaction between the broadleaf-selective herbicide Pyraflufen-ethyl and the grass-selective herbicides. Pyraflufen ethyl was significantly damaging for tedera when combined with haloxyfop or butroxydim. On the 13 August 2018, pyraflufen-ethyl + butroxydim and pyraflufen-ethyl + haloxyfop had a tedera biomass reduction of 83.3 and 80.0%, respectively, while pyraflufen-ethyl + propyzamide and pyraflufen-ethyl alone had 0.0% biomass reduction. On the 14 September 2018, both pyraflufen-ethyl + butroxydim and pyraflufen-ethyl + haloxyfop had a tedera biomass reduction of 60.0%, while also both pyraflufen-ethyl + propyzamide and pyraflufen-ethyl alone recorded no biomass reduction as compared to un-sprayed control.

When combined with any broadleaf weed selective herbicide apart from pyraflufen-ethyl, the grass-selective herbicides caused no significant biomass reduction.

3.3. Experiment 3 (2018). Post-Emergent Herbicides on a 1-Year-Old Tedera Stand

The broadleaf selective herbicides affected the biomass of tedera and broadleaf weeds significantly, mainly capeweed (Table 7). The broadleaf selective herbicides that had least reduction on tedera biomass were flumetsulam + diuron, flumetsulam, prometryn, and diflufenican. The best control of capeweed was achieved with flumetsulam + diuron, imazethapyr, prometryn, and imazamox. Saflufenacil desiccated the whole plot initially, but tedera plants showed good recovery with passage of time.

Table 7. Response of capeweed and a 1-year-old tedera stand to post-emergent broadleaf herbicides applied on 28 June 2018 at Dandaragan.

Herbicides	Rate a.i. g/ha	Tedera Biomass Reduction (%) 13 August 2018 (6 WATA [1])	Tedera Biomass Reduction (%) 14 September 2018 (11 WATA)	Cape Weed Control (%) 13 August 2018 (6 WATA)	Cape Weed Control (%) 14 September 2018 (11 WATA)
Un-sprayed control		0 a [2]	0 a	0 a	0 a
Flumetsulam + diuron	20 + 50	2 a	3 ab	95 e	91 e
Imazamox	35	3 ab	15 cd	32 bc	77 de
Diflufenican	100	3 ab	5 abc	15 ab	38 bc
Prometryn	400	5 abc	3 ab	54 cd	78 de
Flumetsulam	20	6 abc	3 ab	19 ab	60 cd
Imazethapyr	98	13 bcd	13 bcd	64 d	85 de
Oxyfluorfen	120	13 cd	17 de	13 ab	33 b
Pyraflufen-ethyl	8	17 d	8 abcd	12 ab	13 ab
Saflufenacil	23.8	70 e	27 e	100 e	92 e
l.s.d. ($p = 0.05$)		9	10	23	26

[1] WATA = weeks after treatments application. [2] Figures in the columns that share a common letter are not significantly different ($p < 0.05$).

The grass selective herbicides caused no significant reduction in the biomass of tedera, but significantly reduced the grass weeds, mainly annual ryegrass (Table 8). All grass selective herbicides controlled more than 80% of the grasses with no significant differences between treatments on 14 September 2018.

Table 8. Response of grass and a 1-year-old tedera stand to post-emergent grass-selective herbicides applied on 28 June 2018 at Dandaragan (averaged over broadleaf herbicide treatments).

Grass Herbicides	Rate a.i. g/ha	Tedera Biomass Reduction (%) 13 August 2018	Grass Control (%) 13 August 2018 (6 WATA [1])	Grass Control (%) 14 September 2018 11 (WATA)
Un-sprayed control		13	0 a [2]	0 a
Haloxyfop	104	12	49 b	80 b
Butroxydim	45	14	85 bc	88 b
Propyzamide	1000	13	96 c	93 b
l.s.d. ($p = 0.05$)		n.s.	38	17

[1] WATA = weeks after treatments application. [2] Figures in the columns that share a common letter are not significantly different ($p < 0.05$).

3.4. Experiment 4 (2020). Pre-Emergent and Post-Emergent Herbicides on 1-Month-Old Tedera Seedlings

Seedlings in the pre-emergent treatments were counted 1 month after sowing on 29 April 2020 and for post-emergent treatments on 28 May 2020 (Table 8). The pre-emergent application of terbuthylazine at both doses and post-emergent application at the lower dose were highly damaging to tedera and significantly reduced its plant population. The post-emergent application at high dose of terbuthylazine retained a high number of seedlings most likely due to higher number of seeds sown by chance, but not measured. However, those surviving seedlings were severely affected as presented in Table 9.

Comparison of the un-sprayed control and herbicide treatments using visual biomass reduction assessments taken on the 28 May 2020 and the biomass cuts taken on the 25 August 2020 are presented in Table 10. There was no significant effect of time of application or interaction of herbicide by time of application.

Table 9. Number of tedera seedlings/m^2 one month after the application of pre- and post-emergent herbicides.

Herbicides	Rate a.i. g/ha	Seedlings/m^2 (Pre-Emergent) 29 April 2020	Seedlings/m^2 (Post-Emergent) 28 May 2020
Propyzamide	2000	26 a [1]	21 a
Un-sprayed control		23 ab	20 a
Prosulfocarb + S-metolachlor	4000 + 600	20 ab	15 ab
Propyzamide followed by flumetsulam + diuron	1000 + 20 + 90	20 ab	N.A. [2]
Propyzamide followed by flumetsulam + diuron	2000 + 40 + 180	N.A.	20 a
Prosulfocarb + S-metolachlor	2000 + 300	20 ab	20 a
Propyzamide	1000	17 b	21 a
Terbuthylazine	900	6 c	8 b
Terbuthylazine	1800	2 c	20 a
l.s.d. (p = 0.05)		8	8

[1] Figures in the columns that share a common letter are not significantly different (p < 0.05). [2] N.A. Not applicable—Rate was doubled for post emergent herbicide.

Table 10. Visual assessment on tedera biomass reduction taken on the 28 May 2020 and biomass cuts taken on the 25 August 2020, 2 and 5 months after the experiment was sown at Northam.

Herbicides	Rate a.i. g/ha	Visual Biomass Reduction (%)	Dry Biomass (kg/ha)
Un-sprayed control		0 a [1]	6791 a
Propyzamide followed by flumetsulam + diuron	1000 + 20 + 90 [2]	3 ab	6768 a
Propyzamide	2000	5 ab	6560 ab
Prosulfocarb + S-Metolachlor	2000 + 300	14 b	5824 bc
Prosulfocarb + S-Metolachlor	4000 + 600	9 ab	5719 bc
Propyzamide	1000	6 ab	5541 c
Terbuthylazine	900	57 c	2851 d
Terbuthylazine	1800	72 d	1097 e
l.s.d (p = 0.05)		11	897

[1] Figures in the columns that share a common letter are not significantly different (p < 0.05). [2] Rate was doubled for post-emergent herbicide.

Application of propyzamide alone or followed by flumetsulam + diuron had no significant negative effect on plant population and crop biomass (visual) as compared to un-sprayed control. These were the only two treatments that produced tedera biomass at par with un-sprayed control. Prosulfocarb + S-metolachlor resulted in moderate biomass reduction, while terbuthylazine was damaging to tedera.

3.5. Experiment 5 (2020). Post-Emergent Herbicides on 5-Month-Old Plants

Three weeks after spraying on the 21 September 2020, the effect of the 11 herbicides were visually assessed on flowering (Table 11). All the treatments significantly reduced number of flowers except diflufenican and flumetsulam + diuron, as compared to un-sprayed control. A biomass cut of 50 cm × 50 cm quadrat/plot was taken on the 18 December 2020. Despite high variability in the results, the effect of herbicide was significant and four treatments at their highest rate were significantly less productive than the un-sprayed control: MCPA ester + diflufenican, MCPA ester + bromoxynil + diflufenican, bromoxynil + diflufenican, and MCPA ester + bromoxynil.

Table 11. Effect of herbicides on tedera flowering three weeks after application (21 September 2020) and biomass production 15 weeks after application (18 December 2020).

Herbicides	Rate a.i. g/ha	Flowering Reduction (%) 21 September 2020	Biomass (kg/ha) 18 December 2020
Un-sprayed control		0 a [1]	5830 a
MCPA ester + bromoxynil	250 + 250	90 d	5524 a
Diflufenican	100	5 a	5384 a
Diflufenican	300	5 a	4943 ab
Flumetsulam +diuron	40 + 180	10 ab	4430 abc
Bromoxynil + diflufenican	250 + 25	30 bc	4339 abc
MCPA ester + diflufenican	250 + 25	95 d	4268 abc
MCPA ester + bromoxynil + diflufenican	250 + 250 + 25	82.5 d	3914 abc
MCPA ester + diflufenican	750 + 75	97.5 d	3423 bc
MCPA ester + bromoxynil + diflufenican	750 + 750 + 75	100 d	3140 bc
Bromoxynil + diflufenican	750 + 75	47.5 c	2957 c
MCPA ester + bromoxynil	750 + 750	100 d	2851 c
l.s.d. ($p = 0.05$)		21	1948

[1] Figures in the columns that share a common letter are not significantly different ($p < 0.05$).

Diflufenican at both rates and flumetsulam + diuron were the only treatments that had no significant negative effect on flowering or tedera biomass. Either two-way mixes of MCPA ester, bromoxynil, and diflufenican or their three-way mixes reduced number of tedera flowers and biomass significantly.

3.6. Experiment 6 (2020). Post-Emergent Herbicides on 1-Month-Old Seedlings

The pot experiment was harvested eight weeks after spraying 31 post-emergent herbicide treatments. Pots with two or fewer plants remaining were removed from the dataset prior to analysis. The herbicide treatment pyraflufen (label and double label rate) and bromoxynil at the highest rate killed almost all plants in all three replicates; therefore these treatments were not included in the statistical analysis, as they had no data.

The herbicide treatment effect on shoot dry weights and plant height were highly significant with a grand mean of 0.9 g/plant and 8.9 cm, respectively. Treatments including bromoxynil, mesotrione, fluroxypyr, and imazamox + imazapyr reduced or significantly reduced the shoot dry weight in comparison with the un-sprayed control. Regarding plant height, five treatments (imazamox + imazapyr, bromoxynil + diflufenican, fluroxypyr, mesotrione and flumioxazin) were significantly shorter than the un-sprayed control. The six treatments that had diuron either alone or in mixture with other herbicides produced significantly taller plants compared to un-sprayed control (Table 12).

The herbicide treatment effect on root dry weight, average root diameter, and total root volume (root scanning image, Figure 3) were highly significant (Table 12). The mean root dry weight was 0.25 g/plant and flumioxazin, bromoxynil + diflufenican, and mesotrione at both rates and bromoxynil at the highest rate were significantly lower than un-sprayed control. The grand mean for the average diameter was 0.54 mm. The four diflufenican treatments, fomesafen and fluroxypyr at their highest rate and carbetamide had thicker roots, while bromoxynil + diflufenican at both rates and mesotrione and diuron at their highest rate had thinner roots than the un-sprayed control. The total root volume grand mean was 1.95 cm^3, and only both rates of bromoxynil + diflufenican and mesotrione had lower volume than the un-sprayed control.

Table 12. Effect of post-emergent herbicides on tedera shoot dry weight, plant height, root dry weight, root average diameter, and total root volume in a pot experiment at Northam in 2020.

Herbicides	Rate a.i. g/ha	Shoot Dry Weight (g/Plant)	Plant Height (cm/Plant)	Root Dry Weight (g/Plant)	Root Average Diameter/Plant (mm/plant)	Total Root Volume (cm^3/Plant)
Flumetsulam + diuron	20 + 90	1.52	13.17 [1] *	0.41	0.56	2.66
Carbetamide	4140	1.51	11.87	0.32	0.55	2.42
Diflufenican + pyraflufen	100 + 8	1.45	9.36	0.36	0.52	2.07
Diflufenican	400	1.39	9.83	0.40	0.60 *	3.08
Fomesafen	360	1.34	10.74	0.45	0.62 *	3.21
Carbetamide	2070	1.30	12.08	0.41	0.59 *	2.84
Fomesafen	180	1.22	8.39	0.32	0.58	2.03
Flumetsulam + diuron	40 + 180	1.19	12.79 *	0.30	0.56	1.93
Diflufenican	200	1.17	10.20	0.33	0.62 *	2.25
Un-sprayed control		1.11	9.46	0.35	0.51	2.05
Diflufenican + flumetsulam + diuron	50 + 20 + 90	1.09	13.73 *	0.30	0.52	1.74
Diflufenican + pyraflufen	200 + 160	1.06	9.50	0.24	0.48	1.69
Diflufenican + flumetsulam + diuron	100 + 40 + 180	1.01	12.49	0.27	0.49	1.87
Diuron	450	0.96	12.77 *	0.28	0.48	1.64
Diflufenican	50	0.96	6.92	0.25	0.60 *	2.10
Diflufenican	100	0.90	7.46	0.23	0.61 *	2.05
Bromoxynil	250	0.79	7.73	0.19	0.50	1.64
Diuron	900	0.75	12.58	0.20 *	0.44 *	1.26
Fluroxypyr	50	0.75	7.06	0.40	0.58	3.12
Flumioxazin	180	0.71	7.34	0.16 *	0.49	1.18
Imazamox+ imazapyr	10 + 4.5	0.70	6.88	0.20	0.56	1.40
Flumioxazin	90	0.59	6.10 *	0.13 *	0.55	0.97
Imazamox+ imazapyr	20 + 9	0.54 *	3.62 *	0.23	0.56	1.75
Bromoxynil	500	0.54 *	6.64	0.11 *	0.46	0.88 *
Bromoxynil + diflufenican	500 + 50	0.42	5.75	0.06 *	0.39 *	0.47 *
Fluroxypyr	100	0.42 *	2.87 *	0.25	0.64 *	1.99
Bromoxynil + diflufenican	250 + 25	0.33 *	3.38 *	0.05 *	0.44 *	0.52 *
Mesotrione	192	0.22 *	5.50 *	0.07 *	0.43 *	0.59 *
Mesotrione	96	0.20 *	7.19	0.05 *	0.49	0.48 *

[1] Results with a * are significantly different to the Un-sprayed control ($p < 0.05$).

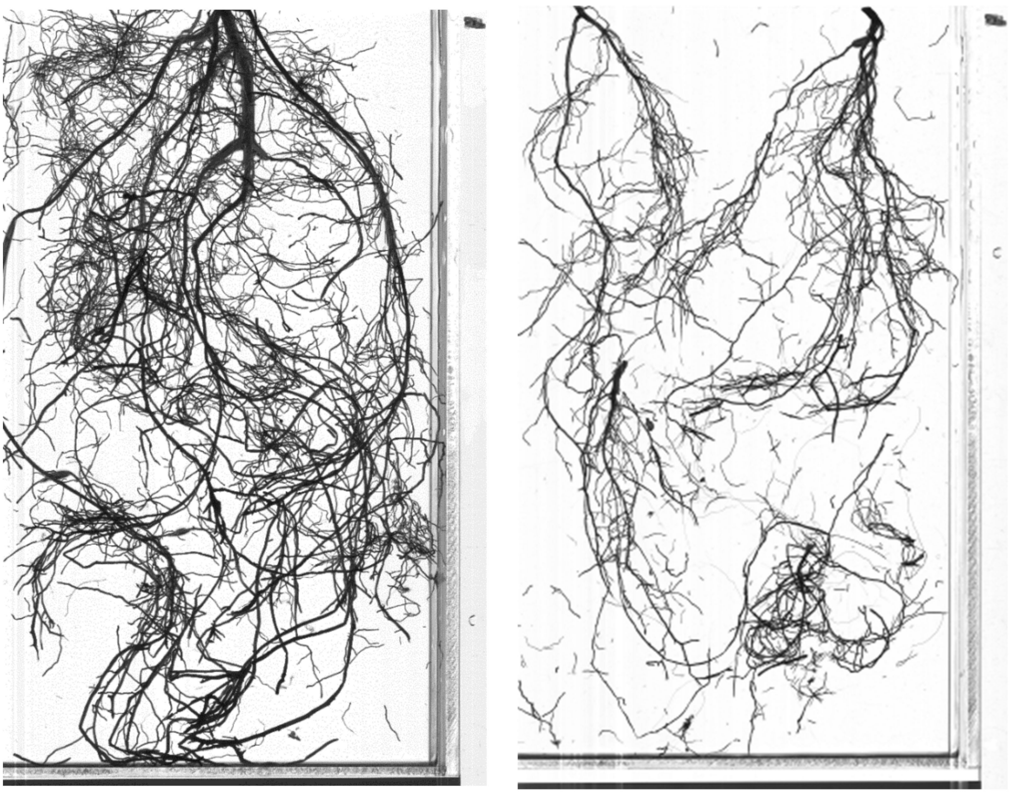

Figure 3. (**Left**) Scanned image of un-sprayed tedera control; (**Right**) tedera sprayed with bromoxynil + diflufenican at 250 + 25 a.i./ha.

3.7. Experiment 7 (2021). Post-Emergent Herbicides on a 3-Year-Old Tedera Stand

Results are presented in Table 13 for visual biomass reduction after 22 treatment application in comparison with un-sprayed control observed 4 weeks (22 July 2021) and eight weeks after application (24 August 2021) and biomass yield taken nine weeks (31 August 2021) on 3-year-old tedera crop.

Table 13. Visual tedera biomass reduction in comparison with un-sprayed control 4 and 8 weeks after treatment application and biomass yield 9 weeks after 22 post-emergent herbicide treatment application at Dandaragan during 2021.

Herbicides	Rate a.i. g/ha	Biomass Reduction (%) 4 WATA [1] 22 July 2021	Biomass Reduction (%) 8 WATA 24 August 2021	Biomass (kg/ha) 9 WATA 31 August 2021
Carbetamide	2070	0 a [2]	0 a	1406 a
Diflufenican + flumetsulam + diuron	200 + 40 + 180	0 a	0 a	1348 ab
Fomesafen	180	3 ab	10 ab	1308 ab
Un-sprayed Control		0 a	0 a	1262 ab
Flumetsulam + diuron + picolinafen	20 + 90 + 37.5	13 bcd	10 ab	1258 ab
Flumetsulam + picolinafen	20 + 37.5	17 cde	3 ab	1212 abc
Fomesafen	360	5 ab	10 ab	1174 abc
Diflufenican + flumetsulam + diuron	100 + 20 + 90	3 ab	10 ab	1173 abc
Diflufenican + flumetsulam + diuron	400 + 80 + 360	3 ab	7 ab	1144 abc
Diflufenican	100	5 ab	3 ab	1134 abcd
Flumetsulam + diflufenican	20 + 100	8 abc	7 ab	1087 abcde
MCPB + MCPA + flumetsulam	600 + 40 + 20	25 efg	37 c	1080 abcde
2,4-DB	500	23 def	50 de	986 abcdef
2,4-DB + flumetsulam	1000 + 20	37 h	60 efg	966 abcdef
Flumetsulam + diuron	40 + 180	3 ab	0 a	922 abcdefg
Picolinafen	37.5	13 bcd	10 ab	859 bcdefg
MCPB + MCPA + flumetsulam	1200 + 80 + 40	30 fgh	53 e	753 cdefg
MCPB + MCPA + flumetsulam	2400 + 160 + 80	35 gh	57 ef	639 defgh
2,4-DB	1000	32 fgh	60 efg	620 efgh
2,4-DB	2000	38 h	67 fg	520 fgh
Flumetsulam + diuron + picolinafen	40 + 180 + 75	13 bcd	13 b	441 gh
Saflufenacil + paraquat	23.8 + 375	50 i	40 cd	434 gh
Glyphosate	450	40 hi	70 g	231 h
l.s.d. ($p = 0.05$)		11	11	496

[1] WATA = weeks after treatments application. [2] Figures in the columns that share a common letter are not significantly different ($p < 0.05$).

There was a highly significant main herbicide effect for the tolerance of tedera for the two visual and biomass cut quantitative assessments in comparison with un-sprayed control. In the July observations, application of carbetamide, fomesafen, flumetsulam, diuron, and diflufenican either alone or in mixture with other herbicides resulted in less than 5% reduction in biomass. Two months after spraying (August), tedera visual biomass was similar to the un-sprayed control for these five herbicide treatments along with picolinafen at the lower rate alone or in majority of the mixtures except a mixture of flumetsulam, diuron, and picolinafen at the higher rate.

At the end of August (nine weeks after treatments application), the tedera biomass was at par with un-sprayed control for the all the above-mentioned treatments with the addition of the lower spraying rates of MCPB + MCPA + flumetsulam and 2,4-DB and 2,4-DB + flumetsulam. The high application rates of 2,4-DB (1000 and 2000 g.a.i./ha) and MCPB + MCPA + flumetsulam, flumetsulam + diuron + picolinafen, saflufenacil + paraquat and glyphosate produced the most long-lasting damage to the 3-year-old-tedera stand. Correlation between visual observations and biomass cut yields at 8 and 9 weeks after treatments application was 0.71.

3.8. Experiment 8 (2021). Pre-Emergent and Post-Emergent Herbicides on 1-Month-Old Seedlings

Plant counts taken on the 14 December 2021 had a grand mean of 54.6 plants/m^2, and there were no significant differences among the herbicide treatments. The effect of the herbicide treatments on the biomass was highly significant, and results are presented in Table 14.

Table 14. Effect of herbicides on tedera biomass (kg/ha) two months after sowing.

Herbicides	Rate a.i. g/ha	Timing	Biomass (kg/ha)
Fomesafen	360	IBS	1397 a [1]
Flumetsulam + diuron	20 + 90	Post-emergent	1320 ab
Fomesafen	360	Post-emergent	1304 ab
Fomesafen	600	PSPE	1296 ab
Diflufenican + flumetsulam + diuron	100 + 20 + 90	Post-emergent	1292 ab
Fomesafen + diuron + flumetsulam	240 + 450 + 40	IBS	1194 abc
Fomesafen	180	Post-emergent	1147 abc
Fomesafen + diuron	240 + 450	IBS	1090 abc
Fomesafen	720	IBS	1023 abcd
Un-sprayed control			1021 abc
Fomesafen	300	PSPE	998 abcd
Fomesafen + diuron	240 + 90	Post-emergent	938 abcd
Fomesafen + clopyralid	240 + 30	Post-emergent	930 abcd
Clopyralid	90	PSPE	902 abcd
Aclonifen + diflufenican + pyroxasulfone	400 + 66 + 100	IBS	883 abcd
Flumetsulam + diuron	40 + 450	IBS	816 bcd
Clopyralid	45	Post-emergent	749 cd
Imazamox + imazapyr	24.8 + 11.2	Post-emergent	549 d
Imazamox + imazapyr	12.4 + 5.6	Post-emergent	538 d
Aclonifen + diflufenican + pyroxasulfone	400 + 66 + 100	Post-emergent	510 d
l.s.d. (p = 0.05)			535
l.s.d. (p = 0.05) (vs Un-sprayed control)			463

[1] Figures in the columns that share a common letter are not significantly different ($p < 0.05$).

All herbicide treatments with fomesafen, flumetsulam, diuron and diflufenican were well tolerated by Lanza® tedera when sprayed pre-emergent (IBS or PSPE) or post-emergent. Imazamox + imazapyr at both rates and aclonifen + diflufenican + pyroxasulfone post-emergent significantly reduced tedera biomass in comparison with un-sprayed control and caused about 15 to 20% yellowing/bleaching symptoms.

4. Discussion

A total of 9 pre-emergent and 44 post-emergent herbicide treatments were evaluated in eight herbicide tolerance experiments from 2017 to 2021. Experiments 4 and 8 evaluated pre-emergent herbicides, experiments 2, 4, 5, 6, and 8 evaluated post-emergent herbicides in one-month-old seedlings and experiments 1, 3, and 7 evaluated post-emergent herbicides in tedera plants 1-year-old or older. Some common weeds in WA such as annual ryegrass, capeweed, and wild radish are controlled by specific herbicides; however, the full list of weeds controlled by each herbicide can be obtained from Moore and Moore [24] or their respective commercial labels in the country of interest.

The first hypothesis that tedera would have tolerance to at least one pre-emergent and one post-emergent herbicide to control grasses such as annual ryegrass was demonstrated. The herbicides evaluated that can control grasses when applied pre-emergent (IBS) were propyzamide, prosulfocarb + S-metolachlor, and aclonifen + diflufenican + pyroxasulfone. Propyzamide at the highest dose (2000 a.i. g/ha) in experiment caused no significant negative effect on tedera plant population and crop biomass. Propyzamide applied at 1000 a.i. g/ha to the whole site of experiment 8 caused no tedera biomass reduction. Prosulfocarb + S-metolachlor (experiment 4) caused no significant reduction in tedera plant numbers, but there was a significant reduction in biomass in comparison with the un-sprayed control. Aclonifen + diflufenican + pyroxasulfone (experiment 8) caused 14% reduction in Lanza® biomass in comparison with the un-sprayed control, but it was not statistically significant. This herbicide being a ready-mix product of three herbicides (e.g., Mateno® Complete), is a promising option from a grass weed control and herbicide resistance management point of view; however, it will require further evaluation before being recommend for use in tedera as pre-emergent IBS application. The three post-emergent grass selective herbicides butroxydim (experiments 1 to 3), clethodim (experiment 1), and haloxyfop (experiments 2 and 3) caused no significant damage to Lanza®. Propyzamide was also evaluated as post emergent (experiments 1 to 4) and caused no damage to Lanza®. Carbetamide is a pre-emergent grass-selective herbicide that was only evaluated as post-emergent in experiments 6 and 7. Results were outstanding with no damage to tedera, and it can be recommended for pre- and post-emergent applications. Prosulfocarb + S-metolachlor was also sprayed post-emergent (experiment 4) and had similar results to the pre-emergent application; there was no significant reduction in plant numbers, but there was a reduction in biomass in comparison with un-sprayed control. All the above-mentioned herbicides except aclonifen + diflufenican + pyroxasulfone, are registered in grain legumes for control of a range of grass weeds including annual ryegrass in Australia. Aclonifen + diflufenican + pyroxasulfone is registered in wheat and barley for control of a range of grass weeds in Australia. Use of carbetamide and propyzamide post-emergent could help manage Group 1 and 2 herbicide resistant annual ryegrass populations during a tedera-phase in rotations with crops in Australia. Resistance to herbicides Group 1 and 2 in annual ryegrass is quite widespread in Australia [25–27].

The second hypothesis that tedera would have tolerance to at least one pre-emergent and one post-emergent herbicide to control the most common broadleaf weeds in southern Australia such as capeweed and radish was demonstrated. The broadleaf tolerance to pre-emergent herbicides is presented in Table 15. Herbicides/rates (a.i. g/ha) in green or yellow were not significantly different to an un-sprayed control, with those in green causing less than 10% biomass reduction and those in yellow causing more than 10% biomass reduction. Those in red had significantly less biomass than the un-sprayed control. The pre-emergent herbicides that had no significant reduction in Lanza® biomass in comparison with un-sprayed were fomesafen to control wild radish pre-emergent and the double mix of fomesafen + diuron and the triple mix of fomesafen + diuron + flumetsulam to control both capeweed and wild radish (pre- and post-emergent). Flumetsulam + diuron or clopyralid to control post emergent capeweed, aclonifen + diflufenican + pyroxasulfone to suppress post emergent capeweed were also statistically similar to unsprayed control, but they caused more than 10% biomass reduction, therefore more research is required to recommend these herbicides at the rate applied.

Table 15. Tedera tolerance to pre-emergent herbicides to control pre- and post-emergent broadleaf weeds. Herbicides/rates (a.i. g/ha) in green or yellow were not significantly different to an un-sprayed control, with those in green causing less than 10% biomass reduction and those in yellow causing more than 10% biomass reduction. Those in red had significantly less biomass than the un-sprayed control.

Herbicide	Exp. 4	Exp. 8
Aclonifen + diflufenican + pyroxasulfone (IBS)		400 + 66 + 100
Fomesafen (IBS)		360; 720
Fomesafen (PSPE)		300; 600
Fomesafen + diuron (IBS)		240 + 450
Fomesafen + diuron + flumetsulam (IBS)		240 + 450 + 40
Flumetsulam + diuron (IBS)		40 + 450
Clopyralid (PSPE)		90
Terbuthylazine (IBS)	900;1800	

The evaluation of tedera tolerance to post-emergent herbicides was conducted on 1-month-old seedlings to maximize the weed control when weeds were still small and most susceptible. Tedera seedling tolerance from five experiments is presented in Table 16. Herbicides/rates (a.i. g/ha) in green or yellow were not significantly different to an un-sprayed control, with those in green causing less than 10% biomass reduction and those in yellow causing more than 10% biomass reduction. Those in red had significantly less biomass than the un-sprayed control.

Table 16. Tolerance of 1 month old seedlings of Lanza® tedera to post-emergent herbicides to control broadleaf weeds. Herbicides/rates (a.i. g/ha) in green or yellow were not significantly different to an un-sprayed control, with those in green causing less than 10% biomass reduction and those in yellow causing more than 10% biomass reduction. Those in red had significantly less biomass than the un-sprayed control.

Herbicide	Exp. 2	Exp. 4	Exp. 5		Exp. 6 [1]				Exp. 8
Aclonifen + diflufenican + pyroxasulfone									400 + 66+ 100
Bromoxynil					250	500	1000		
Bromoxynil + diflufenican			250 + 25	750 + 75	250 + 25	500 + 50			
Diflufenican	100		100	300	50	100	200	400	
Diflufenican + pyraflufen					100 + 8	200 + 16			
Diflufenican + flumetsulam + diuron					50 + 20 + 90	100 + 40 + 180			100 + 20 + 90
Diuron					450	900			
Flumetsulam + diuron	20 + 50	20 + 90; 40 + 180	40 + 180		20 + 90	40 + 180			20 + 90
Flumetsulam	20								
Flumioxazin					90	180			
Fluroxypyr					50	100			
Fomesafen					180	360			180; 360
Fomesafen + diuron									240 + 90
Fomesafen + clopyralid									240 + 30
Imazamox + imazapyr					10 + 4.5	20 + 9			12.4 + 5.6; 24.8 + 11.2
Imazamox	35								
Imazethapyr	98								
Clopyralid									45
MCPA + bromoxynil			250 + 250	750 + 750					
MCPA + diflufenican			250 + 25	750 + 75					
MCPA + bromoxynil + diflufenican			250 + 250 + 25	750 + 750 + 75					
Mesotrione					96	192			
Oxyfluorfen	120								
Prometryn	400								
Prosulfocarb + S-Metolachlor		2000 + 300; 4000 + 600							
Pyraflufen-ethyl	8				16	32			
Terbuthylazine		900;1800							

[1] Colour category assigned based on shoot and root biomass reduction (%).

From the 27 herbicide treatment combinations evaluated with either one or multiple rates and up to five experiments, the most consistently well tolerated herbicide by tedera seedlings was fomesafen up to double the label rate (for other crops). Fomesafen is a herbicide widely utilized to control weeds in soybean crops [28]. Tedera and soybean are genetically close relatives [5,29], therefore the genetic mechanisms of tolerance in soybean might apply to tedera. Fomesafen is not registered for use in clovers and medics and in fact, there are papers reporting damage to white clover (*Trifolium repens* L.) [30] and lucerne (*Medicago sativa* L.) [31]. Further studies are required in WA, but it might be possible to control some of the clovers and medics in tedera stands with fomesafen. Flumetsulam and diuron were tolerated well either alone or in mixes with other herbicides. Diflufenican was well tolerated up to four-times the label rate, but some early damage occurred in experiments 2, 5, and 6. Kelly [20] reported flumetsulam and diflufenican as safe herbicides well tolerated by tedera seedlings. Gray [21] reported 14% biomass reduction for flumetsulam and 30% biomass reduction for diflufenican, which were more damaging than results in our experiments. Different combinations of flumetsulam, fomesafen, diuron and diflufenican can provide good control of capeweed and wild radish. Gray [21] also reported a 55% biomass reduction for imazamox (12.3 a.i. g/ha) and a 30% biomass reduction for imazethapyr (35 g a.i./ha) that agrees with our yellow classification/rating. Prometryn and fomesafen + clopyralid at label rates were also well tolerated but needs further evaluation as they were only evaluated in one experiment. MCPA + bromoxynil were tolerated at label rates, but they caused damage at higher rates. Kelly [20] reported tedera seedling to be susceptible to MCPA (375 a.i. g/ha) and moderately susceptible to bromoxynil (300 a.i. g/ha), while Gray [21] reported 80% reduction in biomass for bromoxynil sprayed at 56 a.i. g/ha. None of these two herbicides should be recommended on Lanza® tedera as these recorded low crop safety margins.

Adult tedera tolerance from three experiments is presented in Table 17. Herbicides/rates (a.i. g/ha) in green or yellow were not significantly different to an un-sprayed control, with those in green causing less than 10% biomass reduction and those in yellow causing more than 10% biomass reduction. Those in red had significantly less biomass than the un-sprayed control.

Table 17. Tolerance of adult Lanza® tedera (one year old or older) to post-emergent herbicides to control broadleaf weeds. Herbicides/rates (a.i. g/ha) in green or yellow were not significantly different to an un-sprayed control, with those in green causing less than 10% biomass reduction and those in yellow causing more than 10% biomass reduction. Those in red had significantly less biomass than the un-sprayed control.

Herbicide	Exp. 1 [1]	Exp. 3	Exp. 7		
2,4-DB			500	1000	2000
2,4-DB + flumetsulam				1000 + 20	
Bentazone	1440				
Bromoxynil	400				
Bromoxynil + diflufenican	250 + 25				
Cyanazine	1080				
Diflufenican	100	100		100	
Diflufenican + flumetsulam + diuron			100 + 20 + 90	200 + 40 + 180	400 + 80 + 360
Flumetsulam + diuron		20 + 50		40 + 180	
Flumetsulam	32	20			
Flumetsulam + diflufenican				20 + 100	
Flumetsulam + picolinafen				20 + 37.5	
Flumetsulam + diuron + picolinafen			20 + 90 + 37.5	40 + 180 + 75	
Fomesafen			180	360	
Glyphosate				450	
Imazamox + imazapyr	24.75 + 11.25				
Imazamox	35	35			
Imazethapyr	98	98			
Linuron	500				
MCPB + MCPA + flumetsulam			600 + 40 + 20	1200 + 80 + 40	2400 + 160 + 80
Oxyfluorfen		120			
Picolinafen				37.5	
Prometryn		400			
Pyraflufen-ethyl		8			
Saflufenacil	23.8	23.8			
Saflufenacil + paraquat	23.8 + 375			23.8 + 375	

[1] Colour category assigned based on biomass reduction (%), yellowing (%), chlorosis (%), and/or necrosis (%).

From the 26 herbicide treatment combinations evaluated with either one or multiple rates and up to three experiments, the most consistently well tolerated herbicides by adult plants of Lanza® tedera were very similar to the herbicides tolerated by the seedlings. Tedera tolerated diflufenican and flumetsulam at up to four-times the label rate, fomesafen up to double the label rate and most two- or three-way mixes with diuron. Different combinations of two or three of these herbicides can provide good control of capeweed and wild radish. Kelly [20] also reported flumetsulam and diflufenican as safe herbicides on mature tedera plants while MCPA and glyphosate caused damage. Moore [22] also supported the safe use of flumetsulam (10-times the label rate) and reported that adult tedera plants can recover with less than 10% biomass reduction four weeks after spraying with 10-times the label rates of imazamox and imazethapyr. Prometryn at label rate was also well tolerated but needs further evaluation as it was only evaluated in experiment 3. Saflufenacil + paraquat desiccated the tedera stand, however tedera as a perennial species was able to recover from being desiccated and grew back very well. This management practice can be very useful in winter when heavy weed infestations of several annual species could be present, and this is an effective way of controlling a diverse range of weeds. Tedera seed crops also showed tolerance to desiccation annually with diquat sprayed at 600 a.i. g/ha before harvesting seed in late spring.

5. Conclusions

Several pre- and post-emergent herbicides well tolerated by tedera to control grasses and broad-leaf weeds were identified. Effective herbicide options are an essential component of an agronomy package for a novel species to agriculture.

To control grass weeds such as annual ryegrass, propyzamide and carbetamide can be safely used as pre- or post-emergent options in tedera. Post-emergent application of butroxydim, clethodim, and haloxyfop can be recommended to control Group 1 herbicide susceptible annual ryegrass and other grass weeds in tedera.

The broadleaf pre-emergent herbicides that can be recommended in tedera were clopyralid to control emerged capeweed, fomesafen to control pre-emergent wild radish and the double mix of fomesafen + diuron, flumetsulam + diuron and the triple mix of fomesafen + diuron + flumetsulam to control pre-emergent capeweed, pre- and post-emergent wild radish, and other broadleaf weeds.

The most consistently well tolerated post-emergent herbicides by seedlings and adult plants of Lanza® tedera were diflufenican, diuron, flumetsulam, fomesafen, and their two- or three-way mixes that will provide good control of pre- and post-emergent capeweed and wild radish.

Desiccants such as paraquat or diquat were also well tolerated by adult tedera plants. Tedera plants showed good quick recovery after desiccation with these herbicides.

The tested post-emergent grass and broadleaf weed-selective herbicides could be applied mixed together (check product labels for compatibility) on tedera for broadening the spectrum of weeds controlled in one-pass-spray except mixing of pyraflufen-ethyl with haloxyfop or butroxydim.

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