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Adapting Syntropic Permaculture for Renaturation of a Former Quarry Area in the Temperate Zone

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Abstract: In Southwest Germany, the renaturation of quarry areas close to settlements is usually based on the planting of native species of trees and shrubs, which are then neither cultivated nor used. This study investigates whether a species-rich agroforestry system based on Ernst Goetsch's syntropic agriculture approach would be suitable for both renaturation in the form of soil fertility improvement and diverse food crop production under temperate climate. The quarry syntropy project was launched in summer 2019. Two shallow stony sections of a spoil heap of the quarry in Ehningen, Southwest Germany were available for demonstration plots. An interdisciplinary project team was set up both to obtain the official permits from five governmental institutions and to begin the study. The demonstration plots were each divided into three broad strips, which differ in three vegetation types: trees, shrubs, and annual food crops. The tree and shrub areas are mainly used for biomass production for a continuous mulch supply on the entire cultivated area in order to rapidly increase soil fertility. The food crops and also partly the trees and shrubs were intended to provide organically produced food (vegetables, fruit, berries and herbs). Most of the trees (eleven species) were planted in November 2019. In March 2020, soil samples were taken (0–30 cm), and a solar-powered water storage system was installed. Currently, the shrub and annual food crop strips are under preparation (pre-renaturation phase). In this initial phase, the priority is fertility improvement of the topsoil through intensive mulching of the existing grassland stock dominated by top grasses and the legumes hybrid alfalfa (*Medicago* × *varia* Martyn) and common bird's-foot trefoil (*Lotus corniculatus* L.). The food crop strip should then start in 2021 after one year of mulching. Depending on the success of growth, the tree strips should then also gain in importance for mulch application in the following years. The strategy is to gradually build up food crop cultivation under organic low-input agricultural practices while simultaneously enhancing the biophysical growth conditions guided by natural succession.

Keywords: agroforestry; biodiversity; bioeconomy; biomass supply; circular economy; organic farming; perennial crops; quarry; syntropy; vegetation restoration

1. Introduction

Agroforestry is considered one of the most important cultivation methods, which not only serves the production of biomass but can also provide many other ecosystem services, such as carbon storage [1,2], crop yield increase [3–5], climate change adaptation [6], biodiversity conservation [7,8], habitat functions [9] and landscape improvement. While there is a lot of information on interspecific interactions within agroforestry systems in the temperate zone [10], the vegetation restoration of quarries by agroforestry approaches has not yet been investigated. In view of the increasing competition for land use [11], it might be important to deal with this in the future, as the areas that are released for renaturation by quarries every year must be enormous in view of the exorbitant production volumes, for example 10 billion tons of concrete per year [12]. So far, these areas are to be renaturalized following the local nature conservation guidelines, i.e., they are left to controlled succession through controlled planting of native tree and shrub species.

Recently, it has been shown that natural succession can be the most reasonable approach for maximum carbon sequestration within the first 20–50 years after establishment [13]. Hence, there might be more complex yet cost-effective renaturation strategies based on natural succession that allow for a much broader spectrum of ecosystem service provision and even food production [14]. This would be of great advantage for the agricultural sector (the production of biomass for food, bio-based products, and bioenergy) as well as for society and the pollinator populations, for example. With increasing land-use conflicts [11], the idea is to set up the establishment of multifunctional agricultural systems on this land. A role model for such an approach could be the syntropic agriculture of Goetsch and Colinas [14]. According to Goetsch and Colinas, "syntropic agriculture" is to be understood as an agricultural strategy according to which soil-physical cultivation parameters such as humus cover, soil fertility, water infiltration and erosion mitigation of agroforestry systems are improved through (i) the introduction of a high diversity of plant species and (ii) an intensive cutting and pruning frequency to foster both light penetration into the system and photosynthesis rate. Following Andrade et al. 2020, this triggers an interplay of natural succession and stratification, resulting in an increased number of vegetation layers consisting of various plant species and stages [15]. Due to this spatial and temporal stratification, syntropic agriculture could lead to an increased biomass productivity compared to standardized mono-cropping-based cultivation methods [14,15]. Syntropic agriculture aims at regaining agricultural productivity of marginal agricultural land in the long term, so that food crops can be cultivated on those areas in the near future [15]. Moreover, this high diversity of plant species and age structures means that syntropic agriculture is more of a transforming agroecology than a conforming agroecology. Therefore, it must be kept in mind that syntropic agriculture requires not only agricultural but also social (socio-economic) adaptation by bridging the gap between agriculture and ecosystems.

The findings by Goetsch and Colinas, on which the methodological approach of this study is rooted, are derived from field trials in the tropics. This means two major differences compared to cultivation strategies for the implementation of syntropic agroforestry systems in the temperate zone: (i) a much shorter growing period induced by a cooler and drier climate, and (ii) different (species-poorer) indigenous plant communities. Therefore, the aim of this study is to share, communicate and may subsequently discuss the concept of developing a syntropic agroforestry approach for restoring a stone quarry in temperate zones based on a preliminary field study conducted in Southwest Germany with the wider scientific community.

2. Materials and Methods

This section presents all the steps of field trial preparation, starting from location selection of the demonstration plots, the basic site characterization in terms of climatical conditions, pedological characteristics and floral biodiversity as well as the selection and installation of the basic infrastructure.

2.1. Location

The experiment is being conducted in the area of the quarry company in Ehningen, Southwest Germany (Figure 1a). Ehningen is located near the river Wuerm, marking the largest glacier extension from the previous ice age. The bedrock is upper shell limestone (Landratsamt Freiburg, 2019), which the quarry company is mining for gravel. An older part of the mine is currently renaturalized and integrated into the typical landscape, consisting of 47% agricultural fields and 34% forest, following the regulations of the federal state Baden-Württemberg. In this area, two demonstration plots (V1, 48°39′57.6″ N 8°55′53.3″ E, and V2, 48°39′51.8″ N 8°55′59.7″ E) (Figure 1b) are available for this experiment. In addition, another area located on a slope (V3, 48°39′52.3″ N 8°55′55.8″ E) (Figure 1b) was selected to account for topographical peculiarities of the given site, but this area was not large enough to establish another demonstration plot. The integration of this field test into the given renaturation plan required official authorization by five regional government departments.

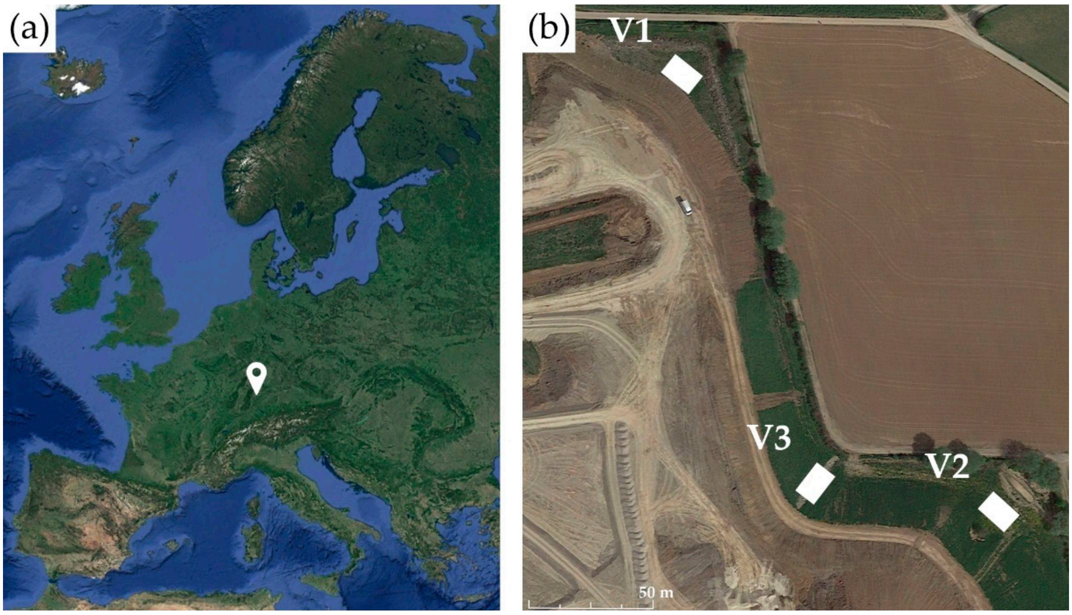

Figure 1. Location of the stone quarry (**a**), and arrangement of the demonstration plots V1–V3 at the stone quarry (**b**).

The region is characterized by temperate oceanic climate (Cfb) with 15 ice days per year, 80 frost days per year, an average annual temperature of 9.6 °C and an average annual precipitation of 672 mm. The latter tends to decline over the past five years due to climate change (Table 1). Initially, soil samples (0–30 cm) were taken in spring 2020 to describe the soil conditions at the beginning of the trial. The samples were frozen until further preparation for laboratory analyses. In addition to the pH value and texture, the contents of macronutrients (C, N, P, K, Mg and Fe) and trace elements (Mo, Co, Cu, Mn, Zn, Cl, Na, B, Ni, Si, Cl, Cd, Pb, As) of the soil samples are to be determined. The content (weight %) of stones in the topsoil was separately determined twice per area. The depth of the crumb was determined mechanically. In terms of soil type, both areas consist of several meters of gravel, sand, and overburden from the construction industry. Over time, a patchy grassland sward has developed on both areas. The botanical composition of this grassland sward was determined in July 2020 (18 July 2020). First, all vascular plant species were determined by species level (except for the genus *Taraxacum*) within a randomly selected sample area of 2 m^2 × 2 m^2. Then, the cover of each vascular plant species (%) was estimated visually. This estimation depends on the stage of phenology.

Table 1. Overview of climatical conditions in the region of the stone quarry over the past eight years (data taken from www.wetter-bw.de).

Year	Average Annual Temperature (°C)	Annual Precipitation (mm)	Climatical Water Balance (mm)	Annual Global Radiation (kWh m^{-2})	Frost Days (d)	Ice Days (d)
2012	9.3	726.7	201.4	928.7	76	20
2013	8.8	922.9	358.2	817.3	93	32
2014	10.4	763.3	173.5	861.3	39	2
2015	10.1	544.9	39.2	747.3	81	7
2016	9.1	646.5	−11.2	1078.3	88	8
2017	9.2	653.9	−51.1	1147.6	90	20
2018	10.2	525.9	−264.3	1234.8	81	19
2019	9.5	591.0	−131.4	1216.1	90	12
Average	9.6	671.9	39.3	1003.9	80	15

The color scaling within the parameters depends on the value.

2.2. Treatments, Field Trial Design and Experimental Stages

Two management methods based on the same establishment procedure were selected as treatments. This means that a mixed culture stand of tree and shrub species was first established on the trial plots, which was then divided into two sub-plots from the third trial year onwards, where two management treatments will be compared: (i) intensive organic farming, and (ii) syntropic agroforestry. The trial is thus divided into two experimental stages:

1. Establishment;
2. Main trial.

The actual start and methodology of long-term experiment evaluation within stage 2 depend on the success of the establishment process. This will be dependent on whether the tree and shrub rows are adequate to provide the vegetable strips with enough mulch material to enable cultivation in accordance with low-input agricultural practices (e.g., no irrigation, no technical weeding measures except mulching etc.), especially in syntropic agroforestry treatment.

Since the size of the three available experimental plots would not have allowed a meaningful integration of repetitions, only one treatment was planned for each plot. This field study therefore serves as a demo experiment. Furthermore, differences in the topographical conditions require a different management method at plot V3 compared with plots V1 and V2, such as those described by Fernandes and Gontijo (2020) [16]. Thus, a different management method was developed for plot V3, the first step of which was the planting of willow cuttings. If the willows grow well, terrace structures are to be designed and built in V3 within the next two years, which are intended to correspond to a syntropic agroforestry treatment. The exact procedure for V3 has not yet been determined.

2.3. Selection of Tree and Shrub Species

The tree and shrub species were compiled on the basis of literature data and the tree species available from the quarry's obligations under nature conservation law (in addition to the trial areas, there were about three hectares of land to be renaturalized) (Table 2). Since there was basically a free choice within these plant species, intensive group work was initially used to determine the objectives to be pursued by the perennial plant society. A multifunctional approach similar to syntropic agriculture [14,15] was chosen, according to which mulch material as well as food and biodiversity support (e.g. pollinators, biocontrol agents) are guaranteed. In accordance with this multifunctional approach, a closer selection of tree and shrub species was then made.

Table 2. Overview of the tree species available for planting in autumn 2019, which have been ordered by the company Baresel (Ehningen, Germany) within the framework of the renaturation. The references used for selecting suitable tree species for this project are also listed.

Trivial Name	Botanical Name	Height of the Young Plant (cm)	References
Sessile oak	*Quercus petraea* (MATTUSCHKA) LIEBL.	>80	[17,18]
European hornbeam [a]	*Capinus betulus* L.	80–120	[19,20]
Wild cherry [a]	*Prunus avium* L.	120–150	[21–23]
Sweet chestnut [a]	*Castanea sativa* Mill.	50–80	[24]
Common whitebeam [a]	*Sorbus aria* (L.) CRANTZ	50–80	[25–28]
Wild Service Tree [a]	*Sorbus torminalis* (L.) CRANTZ	30–50	[29–32]
Wild apple [a]	*Malus sylvestris* MILL. (1768)	80–120	[33–36]
European pear [a]	*Pyrus communis* L.	80–120	[37]
Field maple [a]	*Acer campestre* L.	30–50	[38]
Common dogwood [a]	*Cornus sanguinea* L.	40–70	[39]
Midland hawthorn	*Crataegus laevigata* (POIR) DC.	50–80	[40]
Wayfarer [a]	*Viburnum lantana* L.	40–70	[41]
Red honeysuckle	*Lonicera xylosteum* L.	50–80	[42]
Wild privet	*Ligustrum vulgare* L.	40–70	[43]
Dog Rose	*Rosa canina* L.	50–80	[44]
Buckthorn	*Rhamnus catharticus* L.	50–80	[45]
Blackthorn [a]	*Prunus spinosa* L.	50–80	[46]
Hazel [a]	*Coryllus avelana* L.	50–80	[47]

[a] selected for the tree rows within the demonstration plots V1 and V2.

2.4. Planting Plan and Maintenance of the Trees

The planting plan was developed based on the characteristics of native tree and shrub species. The individual tree and overall arrangement were designed in such a way that the adjacent tree species complement or benefit each other in their above-ground (e.g., crown shape) and underground (e.g., rooting depth, tolerance to temporal water-logging) growth as well as in time. For example, fast growing pioneer tress with high cutting tolerance provide mulch and shelter for emerging fruit trees. In addition, the tree stands were arranged with respect to the cardinal direction with the tree height increasing from southeast to northwest (Table 3).

Table 3. Schematic overview of the arrangement of tree species within areas V1 and V2.

Row 1	Row 2
Walnut (*Juglans regia* L.)	Quince (*Cydonia oblonga* MILL.)
Common dogwood	Willow (*Salix* L.)
European hornbeam	Hazel
Wild Service Tree	Sea-buckthorn (*Hippophae rhamnoides* L.)
Sweet chestnut	Wild apple
European hornbeam	Blackthorn
Field maple	European pear
European pear	Wayfarer
Wild Service Tree	Wild apple
Wild cherry	Common whitebeam
Wayfarer	Common dogwood

The first plantation of native plant tree species was conducted at the experimental sites V1 and V2 on 7 December 2019. For each tree, a hole with a diameter of about 40 cm and a depth of 40 cm was dug with a spade or pickaxe (Figure 2a). The planting distances between trees account for 3 m. Each planting hole was then watered with about 2 L of rainwater (Figure 2b) before the roots of the young plants were placed in the holes and covered with loose soil (Figure 2c).

Figure 2. Impressions from the planting event in December 2019. The planting holes were dug (**a**) and irrigated (**b**) before the seedlings (which were delivered as usual without soil from the nursery) were positioned in the holes and covered with loosened soil (**c**).

The trees were checked at regular intervals and kept free of grasses approximately 50 cm around the stems. The water supply was ensured by the installation of a solar-powered water storage system for irrigating the plants during establishment (Figure 3). Rainwater draining off near the surface is temporarily stored in two 1000-L intermediate bulk containers.

Figure 3. Installation of a solar-powered water pump at plot V2 at the quarry in Ehningen, Southwest Germany during lock-down in April 2020.

In addition, the tree pits were covered with grass mulch regularly (as often as possible) to lower evaporation losses. The management of the trees and shrubs only consist of the formative pruning in the first two to three years.

2.5. Preparation of the Sub-Plots for the Shrubs and Food Crops

The sub-plots for the shrubs and food crops consisted of a grassland sward at the beginning of stage 1. From May 2020, the grassland was mown at regular intervals and the mulch evenly distributed within the sub-plots in order to increase soil cover in the long term. In total, four cuts were performed (cutting height 10 cm) on 7 May, 24 June, 10 August, and 14 October 2020. The change in the species' composition of the grassland sward and its impact on the further course of stage 1 will be assessed in spring 2021.

The demo plots will remain unfertilized by external chemical fertilizers. The nutrient supply through the mulch material should be sufficient to ensure the low-input character of the agroforestry approach. The nutrient status of the soil will be checked annually, beginning with soil sampling in spring 2021. The soil sample analyses should serve to verify the potential use of the site for food crop production. If high levels of heavy metals are present, the use of the plants for human nutrition would be prohibited.

3. Preliminary Results and Discussion

At the time of vegetation analysis of the grassland community, ribwort plantain (*Plantago lanceolata* L.) and the common legume bird's-foot trefoil (*Lotus corniculatus* L.), hybrid alfalfa (*Medicago* × *varia*Martyn) and red clover (*Trifolium pratense* L.) were flowering. Ribwort plantain, black medick (*Medicago lupulina* L.) and dandelions (*Taraxacum* sect. *Ruderalia* Kirschner, H.Øllg. & Štěpánek) were at the stage of seed ripening. The cover of vascular plants accounted for 129% and 133% of the plots V1 and V2, respectively (Table 4).

The vegetation of plot V1 was dominated by the common legume bird's-foot trefoil (Figure 4a), whereas the vegetation of plot V2 was dominated by perennial competitor species such as hybrid alfalfa and couch grass (*Elymus repens* (L.) Gould) (Figure 4b; Table 4). Hybrid alfalfa was sown as part of the renaturation plan on the entire area. The species density of both plots was 17 species 4 m^{-2}. Through a targeted search, each five additional species (outside the sample area) were found in plot V1 (*Medicago lupulina* L., *Galium mollugo* L., *Lotus corniculatus* L., *Lolium multiflorum* Lam., *Arctium tomentosum* Mill.) and in plot V2 (*Potentilla anserina* (L.) Rydb., *Myosotis* spec., *Prunella vulgaris* L., *Linaria vulgaris* Mill., *Achillea millefolium* L.).

Table 4. Cover of plant species (%) within the sample areas (4 m^2) of the grassland communities of plot V1 and V2 on 18 July 2020.

	Plot V1	**Plot V2**
Grasses	15	15
Alopecurus myosuroides Huds.	0	0.2
Arrhenatherum elatius (L.) P.Beauv. ex J.Presl & C.Presl	8	2
Dactylis glomerata L.	2	2
Elymus repens (L.) Gould	0	5
Festuca pratensis Huds.	0	1
Lolium perenne L.	2	5
Poa annua L.	0.5	0
Poa angustifolia L.	2	0
Poa trivialis L.	0.5	0
Legumes	106	63
Lotus corniculatus L.	100	0
Medicago lupulina L.	0.2	0
Medicago × *varia* Martyn	2	60
Trifolium pratense L.	1	1
Trifolium repens L.	3	2
Vicia sepium L.	0	0.2
Forbs	8	55
Achillea millefolium L.	0	0.2
Daucus carota L.	0.2	0
Galium mollugo L.	0.2	0
Hieracium L.	0	0.2
Hypochaeris radicata L.	0.2	0
Plantago lanceolata L.	0	25
Potentilla anserina (L.) Rydb.	0	0.2
Potentilla reptans	0	25
Rosa spec.	0.2	0
Rumex obtusifolius	1	0.2
Taraxacum Sect. *Ruderalia* Kirschner, H.Øllg. & Štěpánek	6	4
Total number of species (4 m^{-2})	17	17

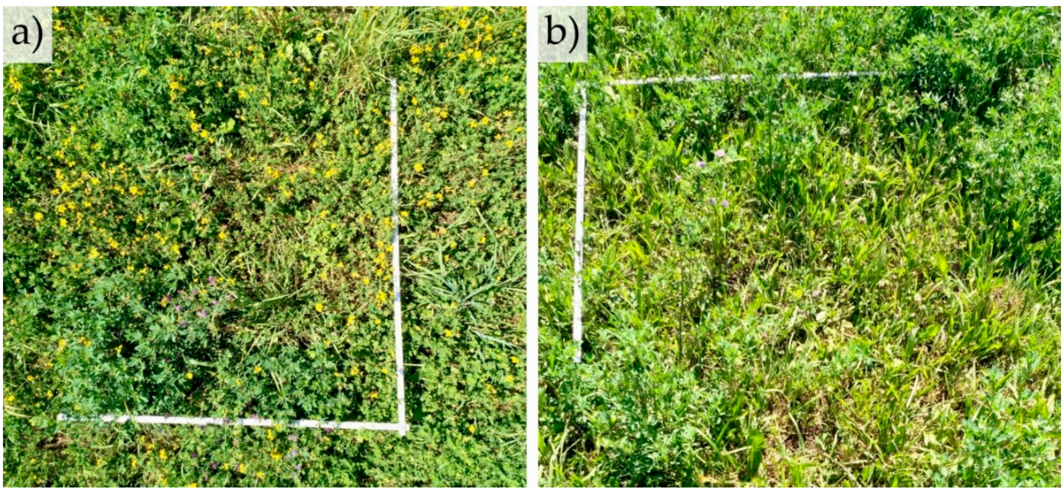

Figure 4. Impressions of the grassland communities on demonstration plots V1 (**a**) and V2 (**b**), 18 July 2020.

The results of the soil analyses of V1 revealed a soil bulk density of 2.1 g cm^{-3} and a high topsoil volume share of stones of 56.7% on site V1 (determined) (Table 5). The topsoil volume of stones on V2 accounted for approximately 40–50% on site V2 (estimated). According to the Joint Research Centre [48], topsoil volumes of coarse material, including rock outcrop or boulders above 15%, are defined as unsuitable for generic agricultural activity. This means that the site can be defined as marginal agricultural land. [49]

Table 5. Overview of topsoil (0–30 cm depth) analyses on demonstration plots V1 and V2. Samples were taken on 18 March 2020.

	Clay	Sand	Silt	Total Carbon	Soil Type	Stones	Earth	Organic Residues
	Weight-% of Dry Matter [a]			Weight-% of Total Dry Matter		Volume-% of Fresh Matter		
V1	20.5	32.2	47.2	9.6	Loam	56.7	42.9	0.4
V2	31.4	14.9	53.7	3.1	Silty clay loam	n.d.	n.d.	n.d.

[a] after destruction of the organic substance.

Eight of the twelve tree species (67%) planted, such as blackthorn (Figures 5 and 6), field maple and wild cherry, survived the plantation and seem to establish well within both demonstration plots (Table 4). On both demonstration plots, the average number of surviving trees (not tree species) per row was seven trees.

However, roe deer have selectively damaged the bark of some of the trees, resulting in the death of these tree species (Table 6). Due to the unexpected presence of roe deer on the heavily fenced quarry area, a countermeasure was applied to help minimize the damage caused by wild animals (roe deer). For this purpose, an electric fence was installed and put into operation around both test areas in early July 2020 (Figures 7 and 8).

Drought conditions in spring 2020 may be responsible for the death of some of the trees. The planting conditions were also sub-optimal in December 2019, given the fact that the weather was very cold and windy, so that many of the fine roots of the plantlets may have been destroyed shortly before planting. Another reason for the death of some of the trees may be the absence of soil and fungal symbionts from the pot in the nursery.

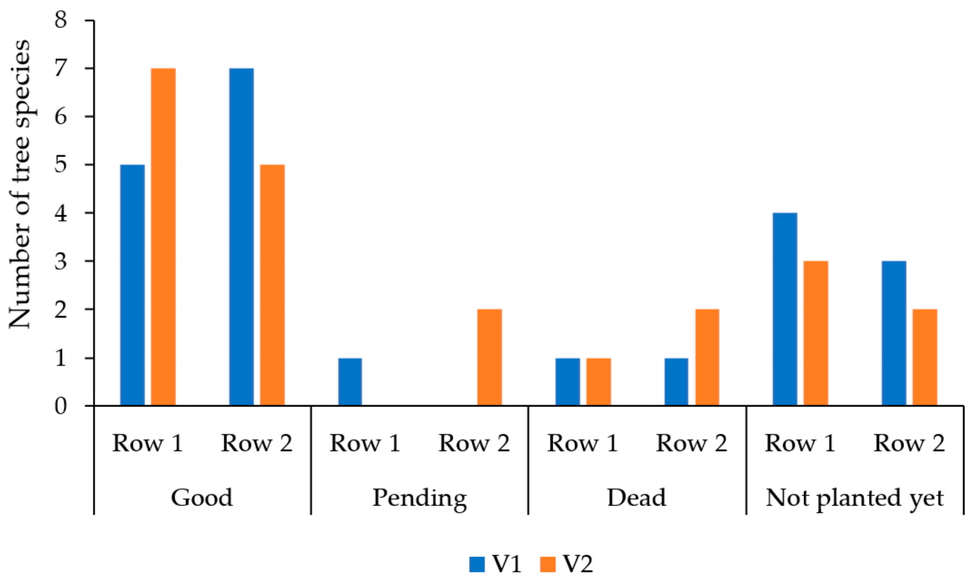

Figure 5. General status of the trees (planted in December 2019) within the two rows of the demonstration plots V1 and V2 on 19 May 2020.

Figure 6. Well-established blackthorn plantlet within demonstration plot V1 on 19 May 2020.

Table 6. Detailed overview of preliminary status of the trees per plot (V1, V2) and row (good = in healthy condition, pending = condition currently unclear, dead = no signs of vitality to be seen, not planted yet = in November 2019, there were no or not enough tree seedlings available).

Tree Species	Plot V1	Plot V2
Row 1		
Walnut	Not planted yet	Not planted yet
Common dogwood	Good	Good
European hornbeam	Dead	Good
Wild Service Tree	Good	Not planted yet
Sweet chestnut	Not planted yet	Not planted yet
European hornbeam	Not planted yet	Good
Field maple	Good	Good
European pear	Not planted yet	Good
Wild Service Tree	Pending	Dead
Wild cherry	Good	Good
Wayfarer	Good	Good
Row 2		
Quince	Not planted yet	Not planted yet
Willow	Good	Good
Hazel	Good	Good
Sea-buckthorn	Not planted yet	Not planted yet
Wild apple	Good	Good
Blackthorn	Good	Good
European pear	Not planted yet	Pending
Wayfarer	Good	Good
Wild apple	Good	Dead
Common whitebeam	Dead	Dead
Common dogwood	Good	Pending

It remains unclear whether the trees would have better established through sowing instead of planting. Here, the trees were planted instead of sown because most of the desired tree species were delivered anyway due to the renaturation of the surrounding area. Furthermore, the plantation of trees usually enables a much faster establishment of the wooden species, which under natural succession conditions could take 25 years and more, depending on the surrounding vegetation [50].

The plantation of willow on all plots, including V3 (Figure 9a), in March 2020 was successful (Figure 9b,c; Table 4) until the drought conditions became too severe in August 2020. Then, most of the willow plantlets showed senescent leaf tissue.

Figure 7. Preparations for the installation of the electric fence at site V2 on 19 May 2020.

Figure 8. View of the demonstration plot V2 with electric fence. Sheep were grazing outside of the plot a few days before this photograph was taken (18 July 2020).

Figure 9. Location of plot V3 (**a**) and impressions of willow plantlets on V3 (**b**,**c**). The stone gutter marks the middle of the area. Willows were planted crescent-shaped, indicated by the green vegetation left over from the last mowing process. The photographs were taken on 18 July 2020.

4. Conclusions

The present study describes the initial stage of the development of a syntropic permaculture concept in the temperate zone of Central Europe and the first steps of its establishment with native woody species. The site selected for this demonstration experiment exhibits marginal agricultural conditions in the sense of shallow stony soil. Following the principle of syntropy, these marginal growth conditions are to be defied by the diversity of the woody stand, which in the ideal case will lead to a win-win situation: the land will be renaturalized and at the same time made reusable for the production of food, fodder and renewable raw materials for material and energy use—depending on which plant species prevails the most.

Of course, the present study has limitations with regard to both the expressiveness of the data and the species diversity within the woody stand. This means that in the case of sowing, it would have been possible to test a much higher number of species on this site for individual and community adaptability. This is also the case for the tropical zone. Nevertheless, important insights can be gained regarding how the selected species will cope with the marginal growth conditions in close association. This is also related to the fact that under temperate conditions the woody species grow much slower and a head start through the establishment by planting helps to gain first insights much earlier compared with an establishment by sowing.

However, the preliminary results presented here already show that some tree species can survive despite the severe rooting and drought conditions. First empirical results on the holistic performance of the management methods investigated here may not be possible for five to ten years. Only then will the woody species begin to provide more and more raw materials (mulch material) and microclimatic effects for the adjacent shrub and vegetable strips. These mutually beneficial interactions between the shrub, bush and vegetable strips would then be one of the main features of the syntropic permaculture in the temperate zone.

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