Field Crops Research 221 (2018) 38–49

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Review

The use of red clover (*Trifolium pratense*) in soil fertility-building: A Review

Patrick McKenna*, Nicola Cannon, John Conway, John Dooley

Royal Agricultural University, School of Agriculture, Food and Environment, United Kingdom

A R T I C L E I N F O

Keywords:
Red clover
Forage legume
Soil fertility
Nitrogen fixation
Allelopathy

A B S T R A C T

Red clover cultivation made significant contributions to soil fertility prior to the introduction of mineral nitrogen fertilizers. Its modern usage lies primarily in forage production, but reintegration into arable systems can enhance sustainability and preserve environmental integrity. Here we review red clovers nitrogen (N) contribution to subsequent crops, its capacity to fix N, and how this N is transferred to subsequent crops. The senescence of the root system following cultivation also contributes to soil organic matter, providing a suite of ecosystem services which are also reviewed. Potential contributions to allelopathic weed control and how this may be utilized to improve weed control is also discussed. Red clover varieties are diverse and can be split into categories of early/late flowering, erect/prostrate and diploid/tetraploid. This use of this diversity to different ends and purposes in fertility-building and the role of plant breeding in optimizing use of genetic resources is reviewed. Management strategies are also diverse; red clover can be grown in monoculture or with companion grasses, it can be harvested for forage or green manured (which can include or omit herbicides) and the consequence of this for soil fertility is discussed. High protein forage production is also a key benefit of red clover cultivation and the economic incentive this may provide to farmers is also reviewed.

1. Introduction

Red clover (RC) is a forage legume cultivated in the temperate world, noted for its high-protein feed (Marshall et al., 2017) and high rate of biological nitrogen fixation (BNF) (Dhamala et al., 2017). This review will focus on the use of RC in soil fertility-building, the contribution it can make to sustainable intensification and the reduction of agriculture's environmental impact. RC was historically cultivated in rotations with other crops to maintain yields, but the advent of mineral fertilizers in the 20th century has displaced much of this use. It remains used for this purpose in many organic systems (Nykanen et al., 2000), but modern usage now lies mostly in grass/clover leys for forage (Abberton and Marshall, 2005). The traditional role of RC as a fertility-building crop remains, however, underutilized and this review will focus on this use.

2. Historical perspective

Wild RC is thought to have originated in South East Eurasia and was first cultivated by farmers in Europe as early as the third century (Taylor and Quesenberry, 1996). Its use in fertility-building and forage production was ubiquitous by the 16th century (Mousset-Déclas, 1995), a dual role cited as having more impact than the introduction of the potato (Fergus and Hollowell, 1960). Replacement of fallowing with RC cultivation increased productivity (Rham, 1860), as did the Norfolk 4 rotation of wheat-turnip-barley-clover (Knox et al., 2011).

The capacity of RC to increase productivity was also recognized by Thomas Jefferson, who wrote in a letter to a friend;

> *'Horizontal and deep ploughing, with the use of plaister and clover, which are but beginning to be used here will, as we believe, restore this part of our country to its original fertility'* (Jefferson, 1817)

Of course, Jefferson wrote this a century before the Dust Bowl and was unaware of the effect 'horizontal and deep ploughing' would go on to have in parts of America (Baveye et al., 2011), but he was ahead of his time in understanding the importance of leguminous rotations in the maintenance of soil fertility. RC cultivation is now almost global. Recommended growing conditions are summarized in Table 1, along with its reported distribution and bioactive compounds.

3. Prospects for red clover in soil fertility-building

Concerns over the potential environmental impact of mineral fertilizers have revived interest in the use of forage legumes to build soil fertility in rotations with cereal crops (Taylor, 2008a), but the high N demand of cereals is a challenge in lower-input systems (Gooding and Davies, 1997). Timely residual N release (i.e. during the spring growth season) is also essential for cereal production. Doel (2013) investigated

* Corresponding author.
E-mail addresses: patrick.mckenna@student.rau.ac.uk (P. McKenna), N.cannon@rau.ac.uk (N. Cannon), J.conway@rau.ac.uk (J. Conway), J.dooley@rau.ac.uk (J. Dooley).

https://doi.org/10.1016/j.fcr.2018.02.006
Received 6 February 2018; Received in revised form 7 February 2018; Accepted 8 February 2018

Table 1
Summary of RC distribution, growth conditions and bioactive compounds.

Global Distribution	North America, Europe, Northern China/Japan, Southern Latin America/Australasia		(Frame et al., 1998)
	Survival Range	Optimal Range	
Soil pH	5.0–8.5	6.0–7.6	(Rice et al., 1977)
Temperature	7–40 °C	20–25 °C	(Frame et al., 1998)
Annual Precipitation	350 mm Upwards	550 mm Upwards	(Frame et al., 1998)
Soil Drainage	Poorly-Well Drained	Well Drained	(Wyngaarden et al., 2015)
Soil Salinity	0–1.5 dS/m	0–0.75 dS/m	(Rogers, 2008)
Bioactive Compounds	Polyphenol Oxidase		(Lushcer et al., 2014)
	Isoflavonoids (Phytoestrogen)		(Boue et al., 2003)

the impact of various fertility-building plants on the yield of subsequent winter and spring wheat in the UK, and reported significantly higher yields following RC cultivation. Moyo et al. (2015a,b) investigated how management practices and companion grasses can significantly affect cereal yields in the same site. These studies are summarized in Figs. 1 and 2.

The results of Figs. 1 and 2 are taken from studies over two years in Gloucestershire, UK. The soil type was calcareous clay loam over Oolitic limestone, commonly referred to as Cotswold Brash (Avery et al., 1980). Wheat was planted following preceding cropping treatments on October 20th and February 19th for Fig. 1, and on 14th October and 14th March for Fig. 2. All crops were sown by hand broadcast, apart from barley, which was drilled. All preceding cropping treatments were for one year and no fertilizers were applied. The data summarized in Fig. 1 (Doel, 2013) indicates RC significantly impacts on subsequent crop production in short time periods. The data summarized in Fig. 2 (Moyo et al., 2015a,b) indicates management and companion grass treatments had significant effects on cereal production. Figs. 1 and 2 demonstrate the fertilizer value of RC cultivation by translating it into grain yield of subsequent crops, which are comparable to conventional mangement in some cases.

4. Nitrogen for contemporary agriculture

Quantification of N inputs is beset by uncertainties and the only reliably accurate statistics for agricultural inputs are for mineral fertilizers; however, some notable estimates have been calculated by Smil (1999b) and Galloway et al. (2004). The European Nitrogen Assessment Project has also made estimates of N cycling in European agriculture using modelling data (Leip, 2011).

Knowledge of the various N sources in global agriculture helps to contextualize the contribution of legumes, but describing the flow of N in agriculture is difficult. Crop residues have many uses (various fuels, fodders and fibers) and no country keeps comprehensive statistics of their uses, making it difficult to assess their contribution to soil N. It is also difficult to calculate the N content of manure from stock under different systems of production, no less to determine what percentage is returned to the soil after manuring. Furthermore, as this review outlines, the numerous methods of measuring fixation in the nodules of legumes have produced varying accounts of the contribution of fixation to the overall N economy. Examples of estimated global and regional N inputs are given in Table 2.

These estimations include both natural and anthropogenic inputs. Understanding how sustainable sources of N derived from BNF can be optimized requires an understanding of the biogeochemical cycling of N in systems using legumes. This can be split into three components; biological fixation of atmospheric nitrogen by Rhizobia bacteria living in the root nodules, the subsequent return of organic N to the soil and the uptake of this by subsequent crops (Cuttle et al., 2003). BNF can be limited or enhanced by soil N status; establishment/persistence, genotypic variation and stresses (Cherr et al., 2006), and mineralization rates are influenced by the C/N ratio of crop residues, management strategies, weather and soil microbe activity (Sarrantonio and Scott, 1998). This means that a variety of agronomic factors must be considered to optimize N contributions from RC cultivation.

5. Biological nitrogen fixation

A number of studies documenting the volume of nitrogen fixed by RC under varying management strategies have been conducted. Tables

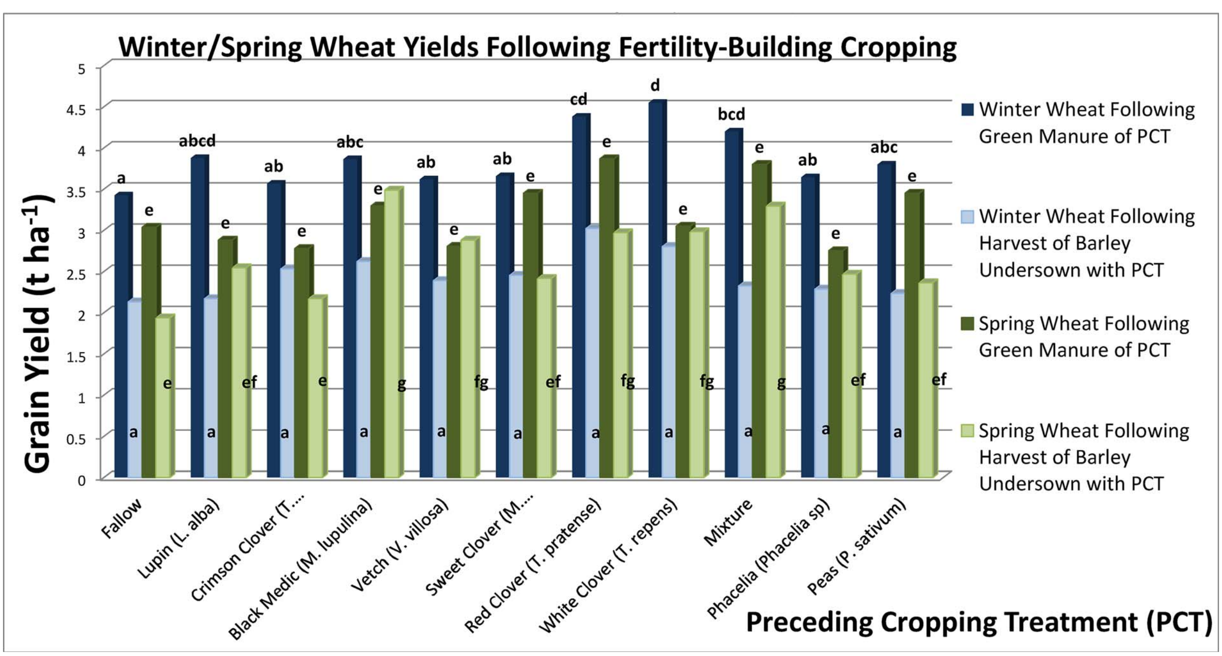

Fig. 1. Impact of various fertility-building crops on winter/spring wheat yields over 6 and 12 months with differing management strategies (Doel 2013).
Fallow results indicated control plots with natural regeneration and 'mixture' indicated 40% RC, 30% sweet clover, 15% lupin and 15% black medic. Bars with the same letters are not significantly different ($P < 0.05$).