Plant Science 262 (2017) 165–168

Contents lists available at ScienceDirect

Plant Science

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

Review article

Genetic mitigation strategies to tackle agricultural GHG emissions: The case for biological nitrification inhibition technology

G.V. Subbarao[a,*], J. Arango[b], K. Masahiro[c], A.M. Hooper[d], T. Yoshihashi[a], Y. Ando[a], K. Nakahara[a], S. Deshpande[e], I. Ortiz-Monasterio[c], M. Ishitani[b], M. Peters[b], N. Chirinda[b], L. Wollenberg[f], J.C. Lata[g], B. Gerard[c], S. Tobita[a], I.M. Rao[b], H.J. Braun[c], V. Kommerell[c], J. Tohme[b], M. Iwanaga[a]

[a] *Japan International Research Center for Agricultural Sciences (JIRCAS), 1-1 Ohwashi, Tsukuba, Ibaraki 305-8686, Japan*
[b] *International Center for Tropical Agriculture (CIAT), A.A. 6713, Cali, Colombia*
[c] *International Maize and Wheat Improvement Center (CIMMYT), Mexico-Veracruz, Elbatan, Texcoco CP 56237, Edo.de Mexico, Mexico*
[d] *Rothamsted Research, Harpenden, AL5 2JO, UK*
[e] *International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Hyderabad, Telangana, India*
[f] *CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), University of Vermont, Burlington, VT 05405, USA*
[g] *Sorbonne Universites, UPMC Univ. Paris 06, IRD, CNRS, INRA, UPEC, Univ. Paris Diderot, Institute of Ecology and Environmental Sciences, iEES Paris, 4 place Jussieu, 75005 Paris, France*

ARTICLE INFO

Keywords:
Greenhouse gas emissions
Nitrification
Nitrification inhibitors
Biological nitrification inhibition
N_2O emissions
Global warming
Genetic mitigation strategies
Breeding nitrogen efficiency
Sustainability
Production systems
Wheat
Sorghum
Brachiaria pastures
Agro-pastoral systems
Paris climate agreement

ABSTRACT

Accelerated soil-nitrifier activity and rapid nitrification are the cause of declining nitrogen-use efficiency (NUE) and enhanced nitrous oxide (N_2O) emissions from farming. Biological nitrification inhibition (BNI) is the ability of certain plant roots to suppress soil-nitrifier activity, through production and release of nitrification inhibitors. The power of phytochemicals with BNI-function needs to be harnessed to control soil-nitrifier activity and improve nitrogen-cycling in agricultural systems. Transformative biological technologies designed for genetic mitigation are needed, so that BNI-enabled crop-livestock and cropping systems can rein in soil-nitrifier activity, to help reduce greenhouse gas (GHG) emissions and globally make farming nitrogen efficient and less harmful to environment. This will reinforce the adaptation or mitigation impact of other climate-smart agriculture technologies.

1. Introduction

Agriculture has become the largest source of man-made greenhouse gases (GHGs) on the planet [1]. It generates 14,000 Tg $CO_2 \cdot eq \cdot yr^{-1}$, about 24% of total GHG emissions [1]. To put this in perspective, CO_2 emissions from automobiles contribute to 14% of global GHG emissions [1,2]. A major portion of agricultural GHG emissions is associated with the production and use of nitrogen (N-fertilizers, based on life-cycle analysis), which is energy and carbon intensive [2]. It is ironic that nearly 70% of N-fertilizers applied to agricultural soils is lost and returned to atmosphere as oxides of N and N_2 (through microbial nitrification and denitrification processes), before the crops can absorb and assimilate it into plant protein with no net benefits to humans [3]. Nearly 80% of global emissions of nitrous oxide (N_2O), a GHG 300 times more potent than CO_2, comes from the production and utilization of N-fertilizers in agriculture [4]. Providing farmers with new nitrogen-use efficiency options requires a major research and development effort, in combination with effective extension approaches.

1.1. The Paris climate agreement

With global food demand projected to double by 2050, agricultural

---

[*] Corresponding author.
E-mail address: subbarao@jircas.affrc.go.jp (G.V. Subbarao).

http://dx.doi.org/10.1016/j.plantsci.2017.05.004
Received 6 February 2017; Accepted 1 May 2017

emissions will grow further, unless agriculture becomes climate-smart [1]. Annual N-fertilizer use is expected to reach 300 Tg by 2050; global N_2O emissions will double compared with present levels and reach 7.5 Tg N_2O—N in such a 'business as usual' scenario [4–6]. The Paris Agreement (PA) signed in 2015, set the goal to reduce GHG emissions by 80% from 2005 levels by 2050 to limit global temperature rise to $< 2\,^\circ C$ [7,8]. Reducing GHG emissions from agriculture is thus critical to meeting PA emission targets [7].

1.2. *Global cropping intensification to maximize yield resulted in weakened soil-health*

Development of fertilizer-responsive crops (e.g. semi-dwarf wheat, -rice, and maize) has transformed global cereal production, but inadvertently unleashed a cascading effect of N-pollution in the environment [8,9]. Farmers in many intensive production systems are being forced to apply more N-fertilizer to sustain higher yields. Selection and breeding under high N-input environments and crop intensification have resulted in the development of nitrate (NO_3^-)-responsive cultivars and high-nitrifying soil environments, leading to a decline in NUE ($<$ 30% at present) in crop production [3,10,11]. Nitrate leaching and N_2O emissions are an indication of weakening soil health (due to declining soil-carbon levels and shifts in soil microbial ecology conducive for accelerated nitrifier-activity) [10,11]. We need a course correction now to increase food production, whilst improving soil health and minimizing GHG emissions.

1.3. *The need for genetic mitigation to tackle N_2O emissions*

Genetically enhanced mitigation technologies that are easily deployable and scalable, to reduce nitrification and N_2O emissions, would make agricultural systems more N-efficient and reduce emissions. Biological nitrification inhibition (BNI) is the ability of certain plant roots to suppress soil-nitrifier activity, through production and release of biological nitrification inhibitors (BNIs) [3]. BNI is a natural plant behavior, found in certain climax ecosystems where plants and microbes compete fiercely for limited mineralized soil-N [12,13].We should learn from nature and introduce these biological mechanisms to manage N-cycling in agricultural systems. Plant roots produce BNIs to suppress nitrifier activity (which converts immobile soil-ammonium (NH_4^+) to mobile soil-nitrate (NO_3^-)) and retain soil-N in NH_4^+ form to facilitate plant absorption and transfer into immobile microbial/organic-N (Fig. 1) [3,10]. Soil-NO_3^-, once formed, is highly prone to leaching, and is also a substrate for soil denitrifying microbes that convert it into N_2O, NO (nitric oxide) and ultimately N_2 gas [3] (Fig. 1) – a net loss for plant production. N_2O is primarily produced during both nitrification and denitrification processes [3] and BNI function suppresses N_2O emissions by reducing nitrification and limiting NO_3^- availability to denitrifiers (Fig. 1) [3,10]. The challenge is to redesign agricultural systems with crops and pastures that produce sufficient BNIs from root systems to suppress wasteful nitrification processes, increase N-flow to the plant and retention in soils, thus significantly improving nitrogen-use efficiency [3,14]. The power of BNI-enabled phytochemical secretions/additions from crop/pasture root systems should be unleashed to limit GHG emissions while sustaining future growth in food production.

2. BNI technology to benefit agriculture and the environment

BNI technology exploits the understanding of BNI chemistry, and its impact on the soil microbiome, to develop genetic components that include BNI-enabled genetic stocks and genetic tools. These would facilitate introduction of BNI traits into major food and forage crops in the near future [3,10,14–18]. Production and release of BNIs from plant roots require the presence of NH_4^+ in the rhizosphere and soil-microsites where NH_4^+ is present, which are also the hot-spots for nitrifier populations [3,10,14,19]. As the BNIs release from roots is localized (i.e. BNI release is confined to parts of the root system exposed to NH_4^+) [14], the delivery of BNIs is thus essentially targeted to where there is a high probability of nitrifier-activity. In addition, sustained release of BNIs from root systems is functionally linked with the uptake and assimilation of NH_4^+, which acts as a switch mechanism for BNI function. This results in a more effective delivery of BNIs to soil-nitrifier sites in the field [20,21]. In addition, the diverse chemical structures of BNI molecules and their multi-mode of inhibitory action on *Nitrosomonas*, could provide a lasting-control over nitrifier activity in agricultural soils compared to synthetic nitrification inhibitors [3,22]. The inhibitory effect from synthetic nitrification inhibitors does not last more than a few weeks at the most (often less than a week) and their delivery in the field is fraught with many challenges. They are expensive to apply and are often ineffective in the field, which may explain the lack of their wide-spread adoption by farmers [23]. BNI technology is suitable for integrated crop-livestock and cropping systems.

2.1. *Crop-Livestock systems*

Brachiaria grasses are the most widely planted forage crops in the tropics with as many as 100 million hectares planted as pastures in Brazil alone [24]. Among forage crops tested, *Brachiaria humidicola* has the highest BNI-capacity and produces brachialactone (a powerful nitrification inhibitor) in its deep-root systems [14]. Each year, from root turnover alone, well-managed *Brachiaria* pastures could add 14 kg brachialactone ha^{-1} and enrich the soil-C by up to 5 t ha^{-1} [25]. In addition, nearly 2.6–7.5 million units of BNI-activity $ha^{-1}\,d^{-1}$ (depending on the genetic stock) is released from roots, equivalent to annual additions of 6.2–18 kg of nitrapyrin ha^{-1} (a synthetic nitrification inhibitor) [10,14]. Field studies with *Brachiaria* grasses showed that while they suppressed nitrification and N_2O emissions [14], the reduced nitrifier activity has improved ^{15}N-retention in soils, ^{15}N-recovery and NUE of maize in an integrated maize-*Brachiaria* (crop-livestock) system for several years [26,27].

2.2. *Cropping systems*

Sorghum, a climate-smart cereal, releases sorgoleone from its roots, which mediates BNI-activity [15,28]. Genetic improvement for enhanced levels of sorgoleone release is one route to develop BNI-enabled cereal production [3,10]. Wheat, the most important food crop (grown on 240 million ha globally), uses about 20% of all fertilizer applied globally [16,17]. However, modern wheat cultivars do not have strong BNI-activity in their root systems [16,17]. Development of BNI-enabled wheat varieties using wild relatives or progenitors as sources of effective BNI-traits can be achieved using chromosome engineering [16,17].Wheat yield potential can be doubled from present levels to reach 20 t ha^{-1}, but requires substantial improvements in NUE to make this economically attractive. The potential for improving BNI-capacity in wheat, sorghum and *Brachiaria* pastures has been illustrated [3,16–18].

2.3. *Deploying BNI technology*

Mitigation strategies/technologies to reduce agricultural GHG emissions must be cost-effective and politically feasible to implement if they are to be adopted widely to reduce costs and deliver benefits to society. For example, mitigation technologies such as alternate wetting and drying in paddy fields can be challenging to implement for social and political reasons [29]. Similarly, the patchy distribution of urine-N (a major N source) in grazed grasslands makes it difficult to control N-losses using synthetic nitrification inhibitors [6]. With 220 million cattle in Brazil alone [30], N-inputs from urine are estimated at 12.8 Tg N y^{-1}(based on the assumption that the average cow excretes 160 g N in its urine per day) and nearly 90% of this N is lost due to