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# On yield gaps and yield gains in intercropping: Opportunities for increasing grain production in northwest China

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ABSTRACT

Wheat-maize relay intercropping has been widely used by farmers in northwest China, and based on field experiments agronomists report it has a higher productivity than sole crops. However, the yields from farmers' fields have not been investigated yet. Yield gap analysis provides a framework to examine land productivity, i.e. the actual yields realized in farmers' fields versus the potential yields when a crop is grown with water and nutrients non-limiting and biotic stresses effectively controlled. In this research, we aim to define yield potentials and yield gaps in intercropping systems, and apply this to an irrigated wheat-maize relay intercrop in Gaotai county (Zhangye city), Gansu province in northwest China. Data from three field experiments (2010 − 2012) were used to calibrate and test crop models for two sole crops and an intercrop. Potential yields were estimated for five years (2010–2014) by model simulations, and actual yields were determined by surveys of 310 farm households in 2014. The main results are: 1) in sole crops, the potential yield of spring wheat is 7.3 t ha$^{-1}$ and the potential yield of maize is 14.2 t ha$^{-1}$; 2) in a wheat-maize relay intercrop with a land area ratio of 0.5 for each crop, the potential yield of wheat is 4.8 t ha$^{-1}$ and that of maize is 12.0 t ha$^{-1}$; 3) comparing the yield in the intercrop and the expected yield (i.e. the yields in sole crops multiplied by the land area ratio in the intercrop for each species), the intercropped wheat gained 32% under potential growing conditions and 67% under actual growing conditions; while the intercropped maize gained 69% under potential growing conditions and 64% under actual growing conditions; 4) farmers achieved 67% of potential yield for sole wheat, and 85% for intercropped wheat; however, farmers achieved only 51% of potential yield for sole maize and 49% for intercropped maize. The farm survey showed that wheat-maize relay intercropping is still widely used by farmers in Gaotai county, and farmers gained extra yield from wheat-maize relay intercropping compared to sole crops, but the gap between potential and actual yields is especially large for maize in this region. Water is likely to be the main limiting factor for maize production despite the irrigation. We conclude by exploring how grain production in Gaotai county would be affected by substituting intercrops by sole crops. We find that the grain production will decrease between 18% to 44% if all the farmers would replace wheat-maize relay intercropping by either wheat or maize sole crop compared to the current land use. Intercropping thus contributes to food production at the regional level, and this contribution can be further increased by narrowing yield gaps.



## 1. Introduction

The world faces the challenge of a population growing beyond 9 billion by 2050. It has been estimated that grain production must increase by ca. 60–70% to meet food requirements (Alexandratos and Bruinsma, 2012; Tilman et al., 2002). At the same time, the production of food for people comes with enormous environmental impacts, including soil degradation, desertification and water pollution (Gregory et al., 2002; Matson et al., 1997). Thus, the development of more sustainable practices is urgent, and one potential strategy is intercropping (Lithourgidis et al., 2011). Intercropping is the cultivation of two or more crop species simultaneously in the same field for the whole or a part of their growing period (Willey, 1990). A meta-analysis study showed that intercropping, including both relay intercropping and intercropping with the same growth duration, uses the land 22% more efficiently than corresponding sole crops (Yu et al., 2015). The main mechanism of high productivity of intercropping is complementary resource use in time and space among different species (Bedoussac et al., 2015; Li et al., 2013; Lithourgidis et al., 2007), and it has played an

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important role in both high and low input agriculture in Asia, Africa and Latin America (Li et al., 2013; Malézieux et al., 2009; Vandermeer, 1989). For example, it is reported that wheat-maize, wheat-soybean and wheat-cotton intercropping are widely used by farmers in China (Li et al., 2001; Li et al., 2013; Zhang et al., 2007). However, in recent years, due to the increasing labour price and labour shift from rural areas to cities, a declining trend of intercropping has been reported (Feike et al., 2012). This could pose a risk to local food security as sole crops generally use land less efficiently than intercrops. Explorative land use studies perform quantitative analysis of different land use strategies to assess the sustainability of production, and to explore optimal land use strategies subject to different goals (van Ittersum et al., 1998). Such studies can reveal the role of intercropping in sustainable food systems in regions where intercropping has played or is playing an important role in food security. Yield gap analysis (van Ittersum and Rabbinge, 1997) provides useful information for such explorative land use studies, by quantifying the scope for future yield increase.

Yield gap analysis aims to examine and benchmark different productivity levels, i.e. the actual yields realized in farmers' fields relative to the potential yield with water and nutrients non-limiting and biotic stresses fully controlled, and to investigate the space for improvement by investing more inputs and better technologies (Bell et al., 1995; Hochman et al., 2013; Laborte et al., 2012; Simane et al., 1994). Yield gaps have been investigated for rice, wheat and maize grain production from regional to global scales (Hochman et al., 2013; Mueller et al., 2012; Neumann et al., 2010; van Ittersum et al., 2013; www.yieldgap.org), and a wide range of yield gaps are observed around the world, ranging from roughly 20% to even 80% of yield potential (Lobell et al., 2009). To date, yield gaps have not yet been defined and quantified for intercrop systems.

The relative performance of intercrops compared to sole crops is often characterized using the land equivalent ratio (LER), which is calculated as the sum of the relative yields of component species in an intercrop as compared to their respective sole crops (Mead and Willey, 1980; Vandermeer, 1989). As LER is a sum of ratios, it is difficult to interpret it in terms of production (kg ha$^{-1}$). Instead, LER is interpreted in terms of land areas needed to achieve total production of a unit area of intercrop using sole crops (ha ha$^{-1}$). And the evaluation using LER is only fair and possible when both sole crops and intercrops are grown under the same conditions. LER is often used by researchers to compare the productivity of sole crops and intercropping, but it is not an easy term to understand for farmers and policy makers. A new approach is required to assess the performance of intercropping in farmers' fields, which is similar to yield gap analysis in sole crops. This approach should be combined with concepts for assessing the potential increase in productivity by using intercrops.

Wheat and maize are two of the world's three most significant cereal crops (Fischer et al., 2012). In addition, the winter wheat and spring maize double cropping system is the main cropping system in northern China, especially in North China Plain (Dai et al., 2013; Ha et al., 2015; Liang et al., 2011a). However, in northwest China, the thermal time is not sufficient to grow wheat and maize after each other in one growing season, while solar radiation is abundant (annually 6000 MJ m$^{-2}$) and irrigation water is locally available from rivers that originate from Qinghai province. Spring wheat and spring maize relay intercropping has been practiced by farmers in Gansu province since the 1960s (Li et al., 2001). According to previous studies, the wheat-maize relay intercropping system has substantial yield advantages compared to sole crops, with an average LER of 1.37 in field experiments in this region (Li et al., 2001; Mu et al., 2013; Song et al., 2006; Yang et al., 2011). However, the potential yields and farmers' yields of wheat and maize in intercrops have not been studied. Water shortage is the main constraint of agricultural production in this region and could be an important reason for differences between potential yields and actual farmers' yields. In Zhangye city, the yearly precipitation is about 160 mm, and agricultural production depends on the snowmelt from Qilian Mountains. However, 50% of the farmland is well irrigated, and much arable land has been abandoned due to water shortage (Zhang et al., 2014). In addition, there are other land use options that may be more economically attractive to farmers than intercropping grain crops, such as seed crops produced for breeding companies, including watermelon, cabbage and maize. These seed crops are competing with land and water for grain production. Thus, the share of land for grain production is currently <40% in all counties in Zhangye city (Shi et al., 2014). Furthermore, wheat-maize relay intercropping has recently decreased in importance in farmers' fields in Wuwei city due to changes in local water management policy, while this region used to be an important grain producer in China (Mao et al., 2012). Thus the effect of changes in land use and cropping systems on grain production is worth investigating.

In this research, we aim to develop new methods to assess farmers' yields in intercrops, to investigate potential yields and yield gaps of wheat and maize in sole crops and in intercrops in northwest China, and to investigate how grain production would change if intercropping was abandoned by the farmers.

## 2. Methods and materials

### 2.1. Concepts

#### 2.1.1. Potential yield in sole crop and in intercropping

In a sole crop, potential yield ($Y_p$ in Table 1) is defined as the yield of an adapted crop cultivar when grown with water and nutrients non-limiting and biotic stress effectively controlled (Evans, 1993; van Ittersum and Rabbinge, 1997). Similarly, in intercrops, the *potential yields* ($IY_p$ in Table 1) are the yields of all the component species that may be attained in a given crop combination and planting pattern, with water and nutrients non-limiting and biotic stress effectively controlled. The potential yield of the intercrops is a set of yield combinations for all component crop species in this intercrop, and it depends on the sowing densities of the crops and their planting configuration. An increase in yield of one species will often be accompanied by a decrease in the yield of the other (due to competition for light, even under otherwise non-limiting provision with water and nutrients). These potential yields can be obtained by crop model simulations or estimated from well-managed field experiments or best farmers' practice (Lobell et al., 2009; van Ittersum et al., 2013). The actual yield is defined as the yield actually achieved in farmers' fields ($Y_a$ for sole crops, and $IY_a$ for intercropping); it is usually obtained by farm surveys or on-farm measurements.

In this study, we consider an intercrop with two species, crops 1 and 2, which are grown with land area ratio $R^1$ and $R^2$. The land area ratio is determined by the sowing density and configuration. If the intercrop is arranged by strips, the land area ratio of each species is calculated by the

**Table 1**
Concepts and notation for potential yield, actual yield, expected yield, yield gain and yield gap in sole crop and intercropping.

| Concept | Sole crop | | Intercropping | |
|---|---|---|---|---|
| | Crop 1 | Crop 2 | Crop 1 | Crop 2 |
| Land area ratio | 1 | 1 | $R^1$ | $R^2$ |
| Potential yield | $Y_p^1$ | $Y_p^2$ | $IY_p^1$ | $IY_p^2$ |
| Expected potential yield | | | $EY_p^1$ | $EY_p^2$ |
| Potential yield gain | | | $\Delta Y_p^1$ | $\Delta Y_p^2$ |
| Actual yield | $Y_a^1$ | $Y_a^2$ | $IY_a^1$ | $IY_a^2$ |
| Expected actual yield | | | $EY_a^1$ | $EY_a^2$ |
| Actual yield gain | | | $\Delta Y_a^1$ | $\Delta Y_a^2$ |
| Yield gap | $Y_g^1$ | $Y_g^2$ | $IY_g^1$ | $IY_g^2$ |

Explanation for descriptors: *R* is for "ratio", *Y* is for "yield", *E* is for "expected", *p* is for "potential", *a* is for "actual", *I* is for "intercropping", *g* is for "gap", and Δ is for "yield gain". The concepts are valid across a wide range of intercropping systems, including fully simultaneous or relay systems, and including strip, row and fully mixed intercropping.